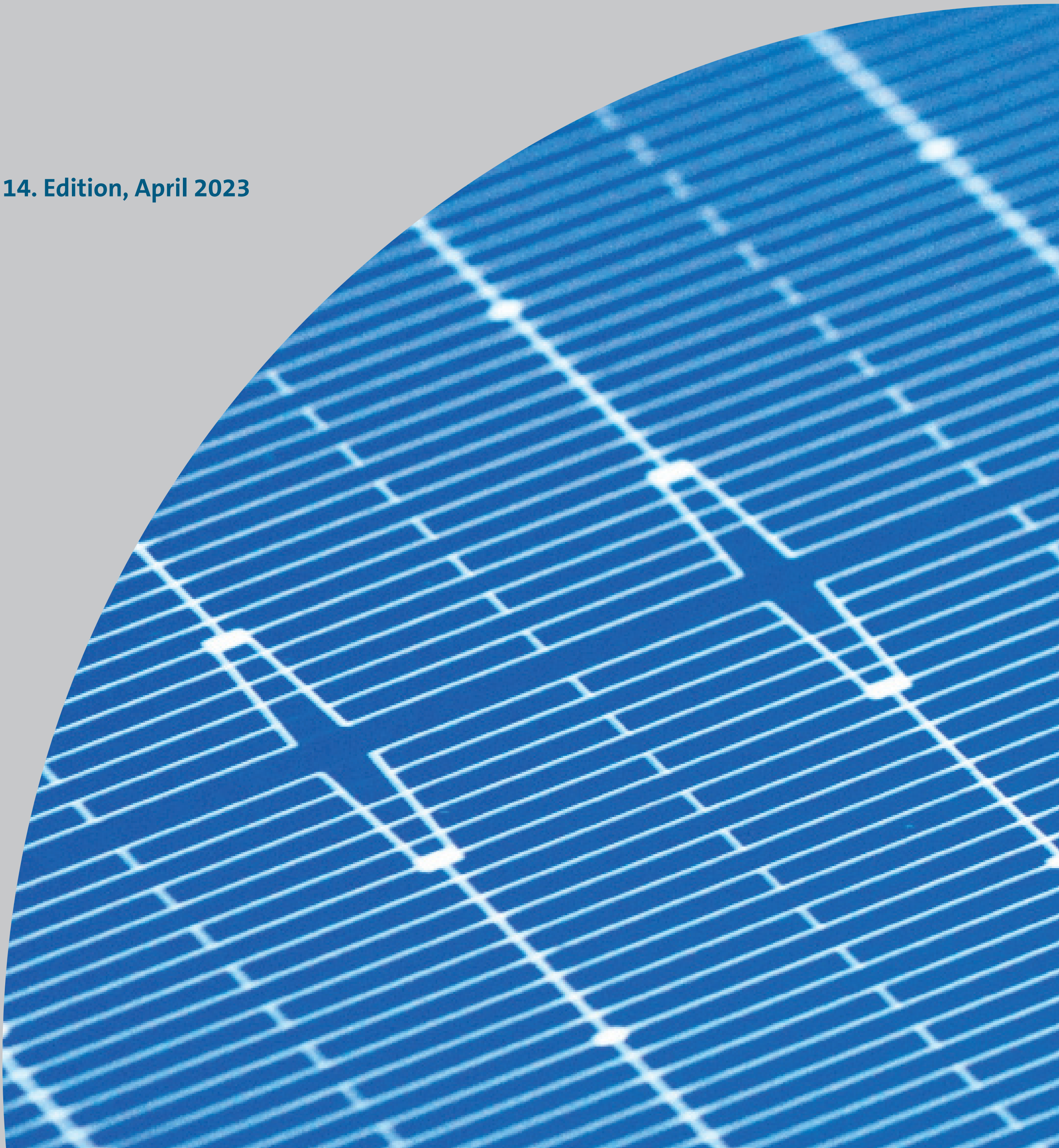
Photovoltaic Equipment

International Technology Roadmap for Photovoltaic (ITRPV)

2022 Results

14. Edition, April 2023



Tongwei entered the market of photovoltaics (PV) in 2006, and after more than 10 years of rapid development, it has become an integrated PV enterprise with high-purity polysilicon production in upstream, high-efficiency solar cell production and high-efficiency PV module production in midstream, as well as experience in PV power plant construction and operation in downstream. It has formed a complete PV new energy industry chain with independent intellectual property rights and leading scale, technology, cost, and quality advantages, building up the vertically integrated layout of the whole PV industry chain. Tongwei continues to strengthen and enlarge its advantages, focusing on the layout of high-purity crystalline silicon, high-efficiency cells, and module products on the manufacturing side and on building a "Fishery & PV Integration" innovative development model on the application side. Tongwei has become an important participant and significant driving force for the development of China and even the global photovoltaic new energy industry.

TW Solar, as the most critical link in Tongwei's PV new energy industry chain, has deeply engaged in the R&D, manufacturing, and promotion of core solar power generation products and has become the world's largest manufacturer of crystalline silicon solar cell and high-efficiency modules with the most advanced technology, production equipment, and the highest level of automation and intelligence in the PV industry. TW Solar has formed a series of fully-flexible, zero-lead, eco-friendly shingled modules and high-efficiency half-cell modules that bring less Levelized Cost Of Electricity (LCOE) for customers at terminal power stations and cover the diverse needs of global customers. With over 20,000 employees on its payroll, TW Solar now has six bases in Hefei, Shuangliu, Meishan, Jintang, Yancheng, Nantong, and the Tonghe project, with an annual cell capacity of 70 GW and an expected 130-150 GW in 2024-2026, of which large-size cell capacity will account for more than 90%. It is seeing an annual capacity of high-efficiency modules of 14 GW and is estimated to reach 80 GW by the end of 2023.

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International Technology Roadmap for Photovoltaic (ITRPV)

Results 2022

Fourteenth Edition, April 2023

Content

1. Executive Summary

The photovoltaic (PV) industry needs to provide power generation products that can compete with both, conventional energy sources and other renewable sources of energy. An international technology roadmap can help to identify trends and to define requirements for necessary improvements. The aim of the International Technology Roadmap for Photovoltaic (ITRPV) is to inform suppliers and customers about anticipated technology trends in the crystalline silicon (c-Si) based PV industry and to stimulate discussions on required improvements and standards. The objective of the roadmap is not to recommend detailed technical solutions for identified areas which need improvement, but instead to emphasize to the PV community the need for improvement, to formulate requirements to meet and to encourage in this way the development of comprehensive solutions. The present, fourteenth edition of the ITRPV was jointly prepared by 61 leading international poly-Si producers, wafer suppliers, c-Si solar cell manufacturers, module manufacturers, PV equipment suppliers, and production material providers, as well as research institutes and consultants. The present publication covers the entire c-Si PV value chain from crystallization, wafering, cell manufacturing to module manufacturing, and PV systems. Significant parameters set out in earlier editions are reviewed along with some new ones, outdated parameters are omitted and discussions about emerging trends in the PV industry are reported.

The global c-Si cell and PV module production capacity at the end of 2022 is assumed to have further increased to 600 GWp due to continued capacity expansions [1]; the market share of about 95% for the c-Si and about 5% for thin-film technologies is assumed to be unchanged [2].

The PV module market in 2022 showed an unprecedented growth to 295 GW. This growth was supported by an improved poly-Si supply and a significant relief in logistics cost [3, 4,].

The c-Si module market shift to mono-Si continued. The implementation of innumerable new module products, dominated by M10, and G12 wafer formats together with bifacial module technology, continued. The weighted average spot market price of c-Si modules at year end 2022 dropped by about 7% compared to the end of 2021. Considering year on year rate, the price reduction is even 14% [5]. All c-Si based products experienced a price reduction and price premiums for high power, bifacial and n-type modules are marginal. The reduced competitiveness of mc-Si based products resulted in a further market share reduction, down to 3%.

Efficiency improvements in passivated emitter rear cell (PERC) technology, the roll out of n-type based products and the deployment of larger wafers in larger module resulted in higher average module efficiencies. The use of larger wafers enabled new module power classes of 600 W and above. Construction of new cell and module capacities in 2022 shifted from PERC to the n-type based tunneling oxide passivated contacts (TOPCon) and silicon heterojunction (SHJ). All new plants will be ready for large cell formats just from the beginning [6]. Manufacturers also invested in the upgrading of older existing production lines for large wafer formats and increase cell efficiencies. The price experience curve continued with its historic learning; the calculated learning rate (LR) is 24.4 %. The PV industry can keep the LR up over the next years by continuing the proven combination of cost reduction measures and implementation of cell perfections, with improved wafer material, improved cell front and rear sides, refined layouts, introduction of bifacial cell concepts, improved module technologies as well as with the introduction of new cell technologies. The introduction of larger cell formats contributes to PV system cost reduction. Improvements in all fields will result in module area efficiency increase: today's mainstream p-type mono-Si based modules reach efficiencies of 21.4% that will increase to 22.75% within the next 10 years, n-type based modules including SHJ provide highest power modules with today's efficiencies of close to 22.5% that will increase up to 24% within the next 10 years. Si-based tandem cells and modules are expected to enter mass production around 2027, starting with module efficiencies of 26%. The combination of optimized manufacturing costs and increased cell and module performance will support the reduction of PV system costs and thus ensure the long-term competitiveness of PV power generation. We experience nowadays that the PV industry is growing to multi-GW markets as projected by ITRPV scenarios. All those aspects are again discussed in this revision of the ITRPV.

VDMA continues the roadmap activity, and updated information will be published annually to ensure comprehensive communication between manufacturers and suppliers throughout the value chain. More information is available at itrpv.vdma.org.

2. Approach

The main c-Si technology value chain elements wafer, cell, and module are discussed in three areas: materials, processes, and products. Data was collected from the participating companies and processed anonymously by VDMA. The participating companies jointly agreed that the results are reported in this roadmap publication. All plotted data points of the parameters reported are median values generated from the input data. In addition to the discussion of parameters linked to crystallization, wafers, cells, modules, we look at the impact and trends for PV systems and discuss trends in smart fab manufacturing.

2.1. Materials

The requirements and trends concerning raw materials and consumables used for wafer, cell, and module manufacturing are described in these subsections. Reducing the consumption or substitution of some materials will be necessary in order to ensure availability, avoid environmental risks, reduce costs, and increase efficiency. Price development plays a major role in making PV-generated electricity competitive with other renewable and fossil fuel-based sources of energy.

2.2. Processes

New technologies, new materials, and highly productive manufacturing equipment are required to reduce production costs. By providing information on key production technologies and by discussing process parameters to optimize the wafer production, to increase cell and module efficiency as well as module power output, this roadmap constitutes a guide to new developments and aims to support their progress. The subsections on processes identify manufacturing and technology issues for each segment of the value chain. Manufacturing topics center on raising productivity, while technological developments aim to ensure higher cell and module efficiencies.

2.3. Products

Each PV value chain element contributes to final products. The products subsections therefore discuss the anticipated development of the value chain elements ingot, wafer, c-Si solar cell, and module over the coming years.

3. PV Learning Curve

It is obvious that cost reductions in PV production processes will also result in price reductions [7]. Fig. 1 shows the price experience curve for PV modules, displaying the average module sales prices - at the end of the corresponding period - (in 2022 US$/Wp) as a function of cumulative module shipments from 1976 to 12/2022 (in MWp) [8, 9]. Displayed on a log-log scale, the plot changes to an approximately linear line until the shipment value of 3.1 GWp (shipments at the end of 2003), despite bends at around 100 MWp. This indicates that for every doubling of cumulative PV module shipment, the average selling price decreases according to the LR. Considering all data points from 1976 until 2022 we found an LR of about 24.4% - again an increase compared to the 24.1 % in the 13th edition. The large deviations from this LR plot in Fig. 1 are caused by market fluctuations between 2003 and 2012 as well as in 2016 and 2018.

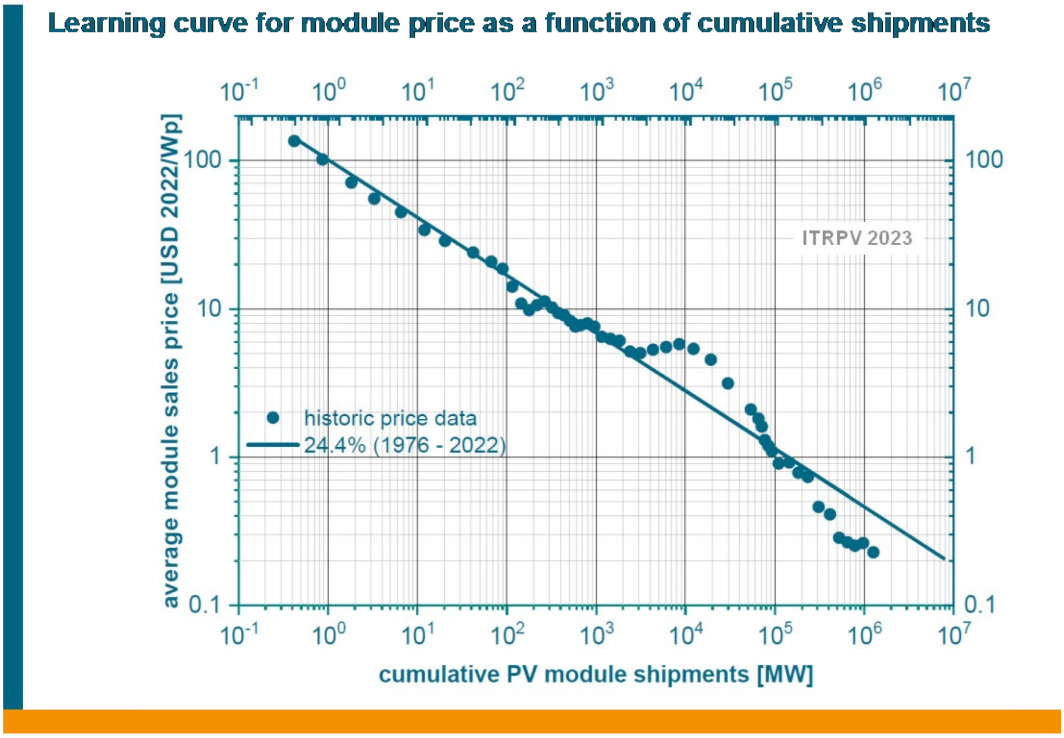


Fig. 1: Learning curve for module spot market price as a function of cumulative PV module shipments.

The last data point indicates the module shipment volume and average spot market price at the end of 2022. The 2022 shipment volume was calculated to be 295 GWp - Installation of 258 GWp [9] plus 37 GWp not yet installed (i.e., in warehouses, at customers, and in transit) until year end. In the EU, for instance, the 2022 difference between shipments and installations was at least about 20 GW [10,11]. Based on this data the cumulative shipped module power at the end of 2022 was calculated to be 1,267 GWp. The corresponding worldwide installed cumulative module power by the end of 2022 is 1,198 GWp after 940 GWp in 2021 [9]. As described in chapter 4, the calculated average module spot market price at the end of 2022 is 0.228 US$/Wp.

4. Cost Consideration

Fig. 2 shows the price development of mono-Si modules from December 2017 to December 2022 with separate price trends for poly-Si, mono-Si wafers, cells (≤ M6, > M6, avg.), and modules [12].

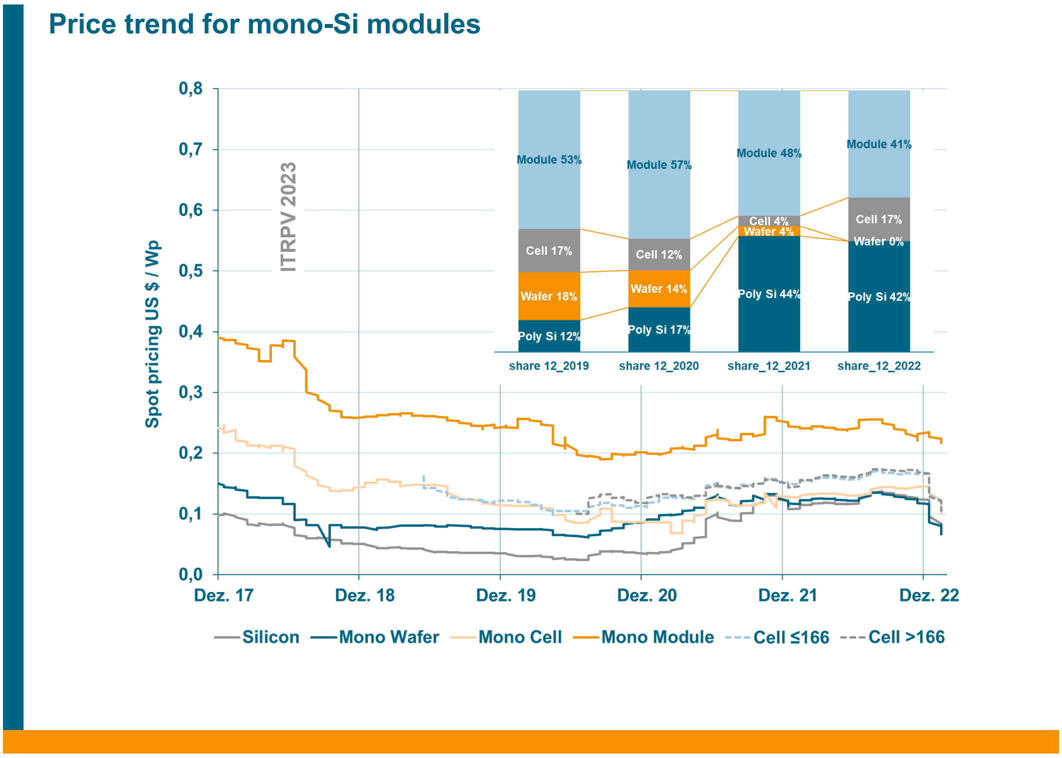


Fig. 2: Spot market price trends for poly-Si, mono-Si wafers, cells, and modules.

Module production capacity at the end of 2022 is assumed to be about 600 GWp due to continued capacity expansions [1]. So, the PV module market showed an unprecedented growth to 295 GW. This growth was supported by an improved poly-Si supply and a significant relief in logistics costs [3, 4]. All c-Si based products experienced a price reduction and price premiums for high power, bifacial and n-type modules are marginal. The reduced competitiveness of multicrystalline silicon (mc-Si) based products resulted in a further market share reduction of mc-Si to 3%.

Since end of 2020, publicly available price data have been reporting in addition to mono-Si and mc-Si standard module prices, also prices for cells and modules with M6, M10, and G12 wafer formats as well as for bifacial modules. Therefore, average module prices reported in Fig. 1 are calculated as weighted average of 5 different product groups: standard mc-Si modules, standard mono-Si modules, mono-Si modules with superior power rating, bifacial mono-Si modules, and n-type based modules.

This average module prices for 12/2022 are calculated based on the following numbers:
0.207 US$/Wp for mc-Si modules, 0.227 US$/Wp mono-Si modules, 0.228 US$/W for modules with superior power rating and 0.230 US$/Wp for bifacial and n-type based modules [12, 13]. We calculated 0.228 US$/Wp as weighted average spot market price for c-Si modules at year end of 2022 based on 2022 ITRPV findings in Fig. 9, Fig. 10, and Fig. 57. The assumed market shares are therefore: 30% for standard mono-Si modules, and 22% for superior power rating modules, 15%/30% for n-type based and bifacial modules respectively, as well as 3% for mc- wafer based modules.

Fig. 2 shows the comparison of the proportion of prices attributable to silicon, wafer, cell, and module price for December 2019, 2020, 2021, and December 2022 respectively. The price for c-Si modules at year end 2022 dropped by about 7% compared to the end of 2021. Considering year on year rate, the price reduction is even 14% [5]. The overall price share of poly-Si has stayed quite unchanged since 2021 due to the continued high poly-Si prices [3, 14, and 15].

The non-silicon module manufacturing costs are mainly driven by consumables and materials as discussed in the c-Si PV module cost analysis in the 3rd edition of the ITRPV [16]. Those prices also stayed high in 2022 and the situation is not expected to change rapidly. Achieving cost reductions in consumables and pre-cursor materials will be more difficult but must be continued. Improving productivity and product performance will stay in the focus resulting in continued pressure on existing and new installed manufacturing lines [17].

The known three strategies, emphasized in former ITRPV editions help to address this challenge:

- Improve module area efficiency without significantly increasing the processing cost.
- Continue the cost optimization per piece along the entire value chain by increasing the Overall Equipment Efficiency (OEE) of the installed production capacity, by implementing upgrades and new production capacities, by using Si and non-Si materials more efficiently, and ensuring higher OEE of new installed capacities.
- Introduce specialized module products for different market applications (i.e., tradeoff between cost-optimized, highest volume products and highest efficiency, higher price roof-top applications or even fully customized niche products).

The first point implies that continuous cell efficiency improvements need to be implemented not only with the new, larger wafer formats but in parallel with new module concepts to further improve the module area efficiency. To enable cost efficient manufacturing this must be implemented with lean processes to optimize capital expenditures. It will remain difficult to introduce new, immature technologies that do not show reductions of the cost per Wp from the beginning.

5. Results of 2022 | Crystallization and Wafering

5.1. Materials

Poly-Si remains the most expensive material of a c-Si solar cell as discussed in chapter 4. Siemens process will keep today's mainstream position. Fluidized Bed Reactor (FBR) process will remain the 2nd technology of choice to produce poly-Si today.

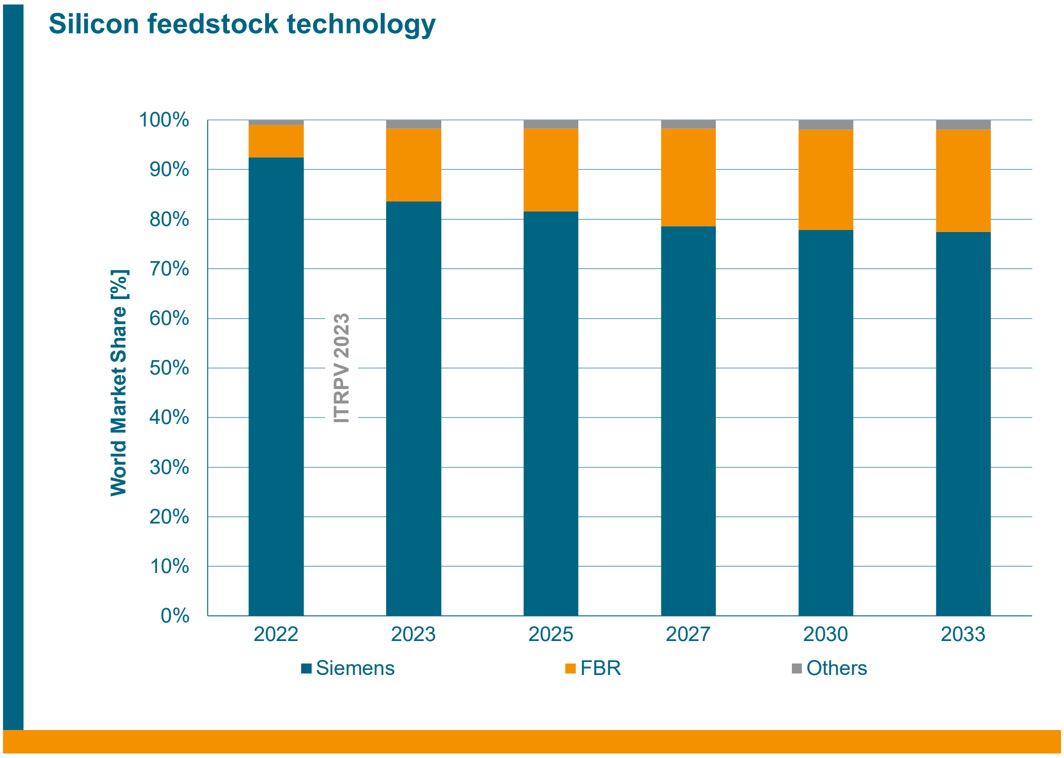


Fig. 3: Expected world market share of poly–Si feedstock technology.

Based on our results, the market share of FBR poly-Si to about 6% in 2022 as shown in Fig. 3, This is close to the analysis in [18]. We expect that this share will increase to about 20% within the next 10 years against the mature and further optimized Siemens process. Other technologies like upgraded metallurgical grade-Si (umg-Si) are not expected to yield significant cost advantages compared to the two matured poly-Si technologies over the coming years. Nevertheless, they are expected to stay available in the market.

Fig. 4 shows the average consumption of poly-Si to produce silicon wafers. A 160 µm thick 166 mm x 166 mm mono-Si wafer weighs about 10.1 g. That means 14 g or 140% of remaining Si in the wafer were necessary in 2022 to produce a standard M6 mono-Si wafer. All wafer formats will consume significant less silicon within the next 10 years. Expected reductions are in the range of 25% for M6 and M10 and about 30% for G12 respectively. This reduction will be realized by improving the yields in crystallization and wafering, by further reduction of kerf loss, and, most importantly, by further thickness reduction as shown in Fig. 6 to Fig. 8.

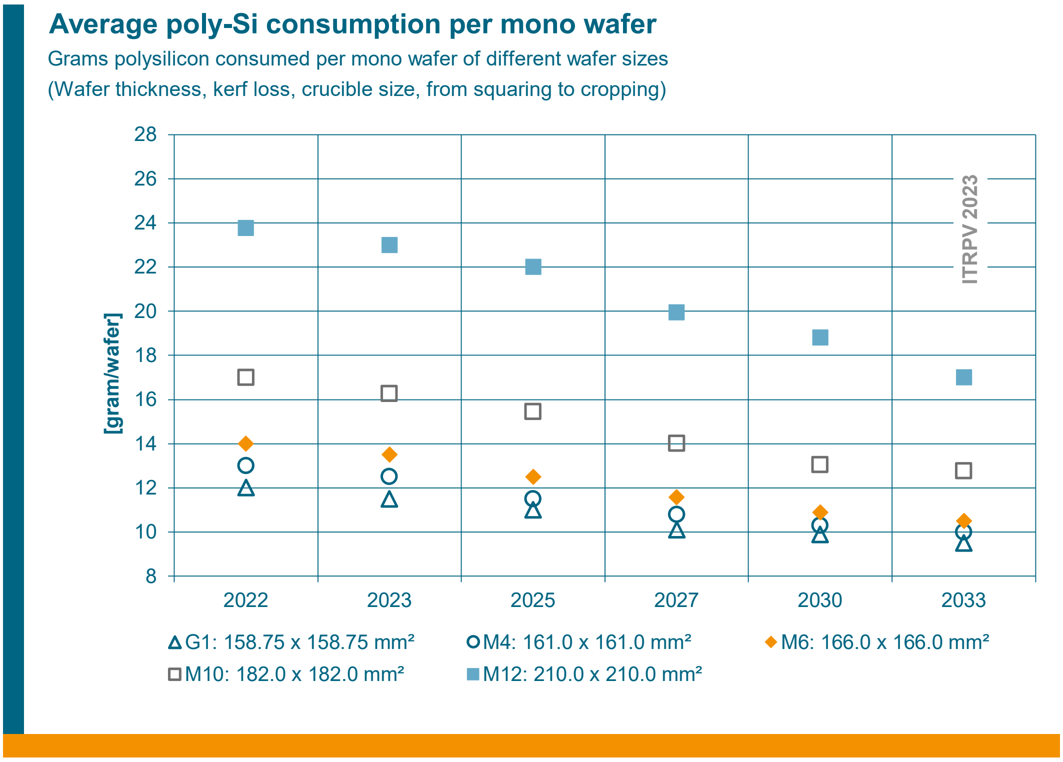


Fig. 4: Average poly-Si consumption for mono-Si wafers with diamond wafer sawing technology.

Fig. 5 shows the poly-Si consumption per Wp for p-type PERC wafers of the corresponding wafer sizes.

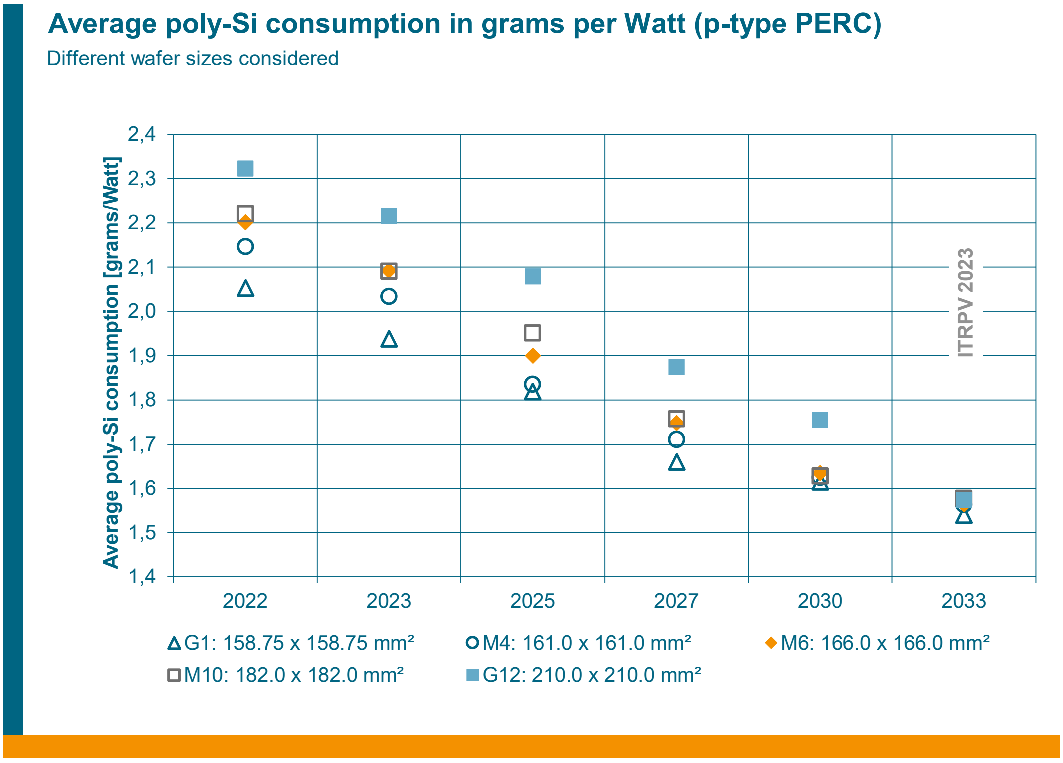


Fig. 5: Average poly-Si consumption for mono-Si wafers for p-type PERC (efficiencies according to Fig 38).

Cell power is calculated according to the cell efficiency trend for PERC in Fig. 38. The trend in Fig. 5 shows that, based on current assumptions, M10 and G12 format not automatically consume to a relatively lesser extent poly-Si per wafer. This emphasizes the need for even faster improvements for the larger formats in order to realize their benefits in levelized cost of electricity (LCoE) reduction not primal on power plant level but also in further module cost reductions by more efficient use of poly-Si. Nevertheless, in 2023, M10 consumes similar as much poly-Si as M6. In 10 years, the poly-Si consumption will be <1.6g/W for all formats.

5.2. Processes

5.2.1. Crystallization

It is possible to increase the throughput of the crystallization process by changing the common sizes of the ingots and by growing more crystals with the same crucible. The trends to larger ingot mass as discussed in former ITRPV editions continue. Czochralski (Cz) growth with recharging is found to be the mainstream technology in crystallization.

The mainstream doping element for p-type mono-Si material is Gallium. We found that Boron as dopant for p-type material disappears in 2023. The biggest advantage of gallium doping is the significant reduction of Light Induced Degradation (LID) of p-type material [19].

5.2.2. Wafering

The landscape in wafering technology changed completely during the last years. The triumphal procession of diamond wire sawing (DWS) for mono-Si and mc-Si wafering, was a significant improvement in terms of wafering process stability and cost reduction. Since its introduction, DWS has enabled significant reductions of the kerf width and contributed therefore to the improved usage of poly-Si, as discussed in chapter 5.1.

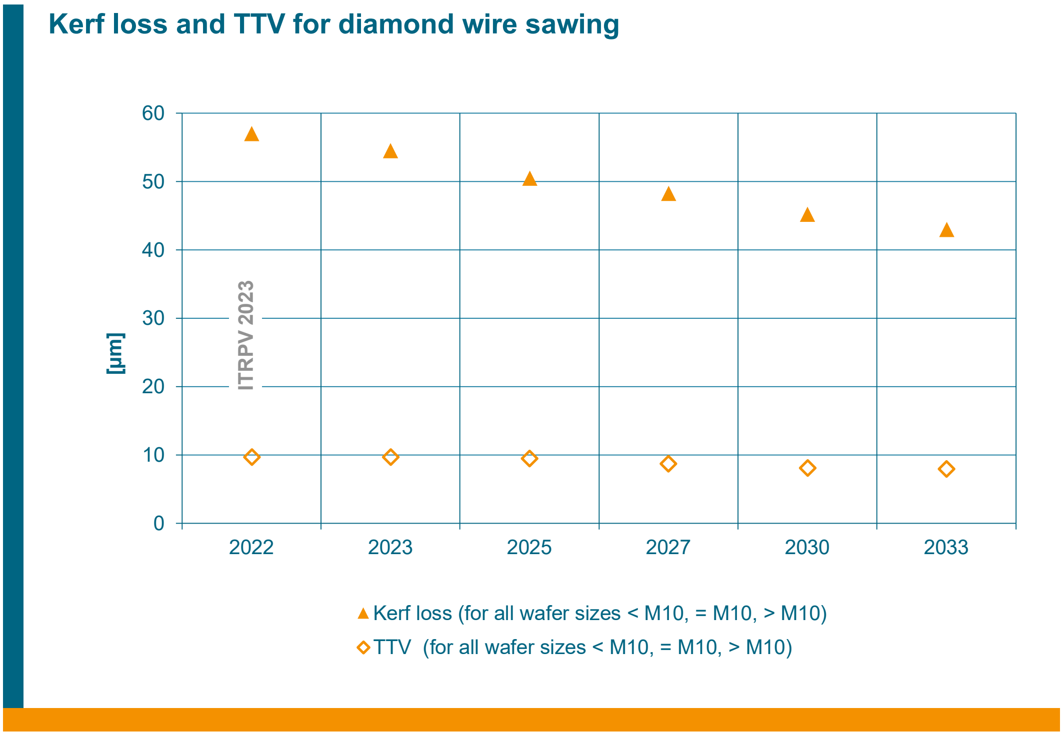


Fig. 6: Kerf loss and Total Thickness Variation (TTV) trend for diamond wire sawing of all wafer formats.

The shift was enabled by the fast improvement of appropriate wet chemical processes for saw damage removal and texturing. Based on the results, kerfless wafering technologies are still not seen to contribute to the market share significantly. DWA is the mature technology. Fig. 6 describes the trend for kerf loss and for Total Thickness Variation (TTV) for all wafer sizes. A kerf width of 55 µm is standard in 2023 with DWS. Large wafer formats benefit from this trend particularly. The kerf loss is predicted to decline to 43 µm within the next 10 years. TTV of 10 µm is reached by today, and this is in line with the requirements of the 13th edition.

5.2.3. Process Improvement Trends

Thinner wafers, reducing kerf loss, increasing recycling rates, and reducing the cost of consumables, will yield in cost savings. Wire diameters will be reduced continuously and there will be more recycling of silicon and diamond wire over the next years. Increased tool throughput will improve the productivity in crystallization and wafering on top of the yield enhancements by reduced kerf loss. This contributes to further cost optimization. All technologies are expected to realize between 10% and 30% throughput increase within the next 10 years. New kerfless wafer manufacturing approaches are still being studied.

5.3. Products

Using poly-Si as efficient as possible has been key for further cost reduction for c-Si cells and modules especially since 2021 when poly-Si run short at exorbitant prices. Reducing the as-cut wafer thickness is now becoming the method of choice to continue cost savings.

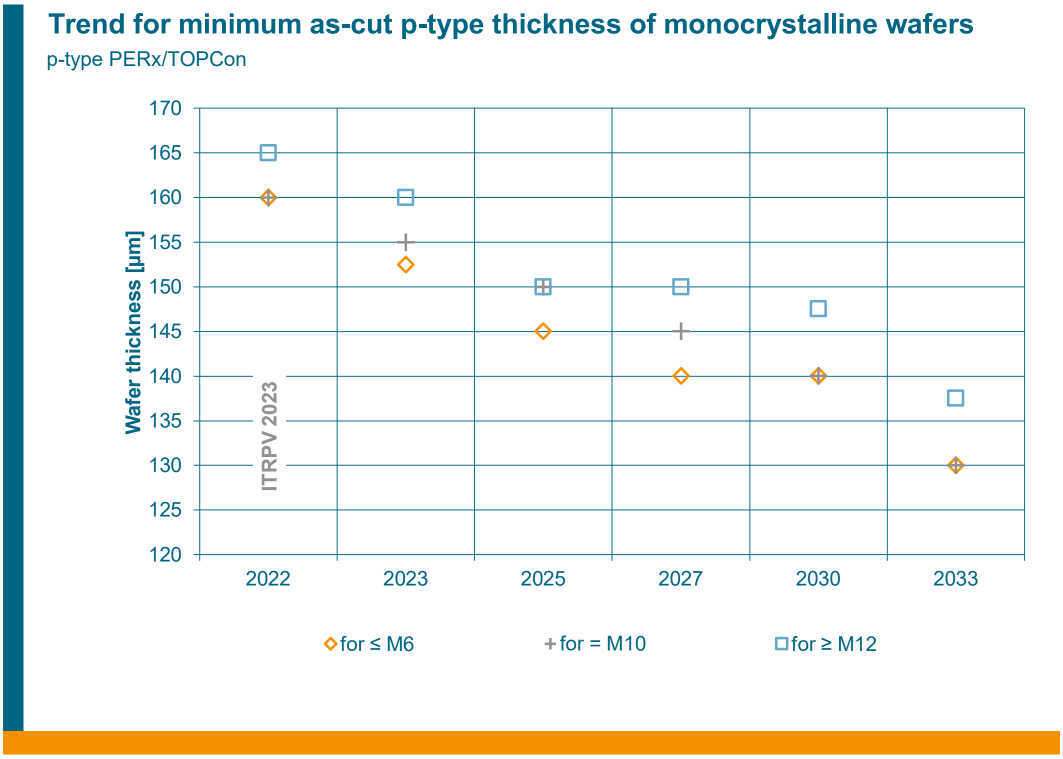


Fig. 7: Predicted trend for minimum as-cut wafer thickness of p-type c-Si wafers with different dimensions.

Fig. 7 and Fig. 8 show the expected trend for minimum as cut wafer thickness for p- and n- type as cut mono-Si wafers and wafer sizes. Since years of stagnating wafer thickness, we have been seeing since 2020 that mono-Si wafer thickness reduction is making huge progress, even ahead of the trend shown in the 12th edition of the ITRPV. Wafer thickness of 160 µm was the standard in 2022 for p-type mono wafers with ≤ M6 and M10 wafer dimension. M6 wafers are expected to get a faster thickness reduction. A minimum wafer thickness of 130 µm will be reached for M6 and M10 in 2033 when 137 µm will be reached for ≥M12 as shown in Fig. 7. Mono-Si wafers ≥G12 wafers are between 5 µm and 7.5 µm thicker than mono-Si wafers in today's dominating M10 format. The corresponding cell

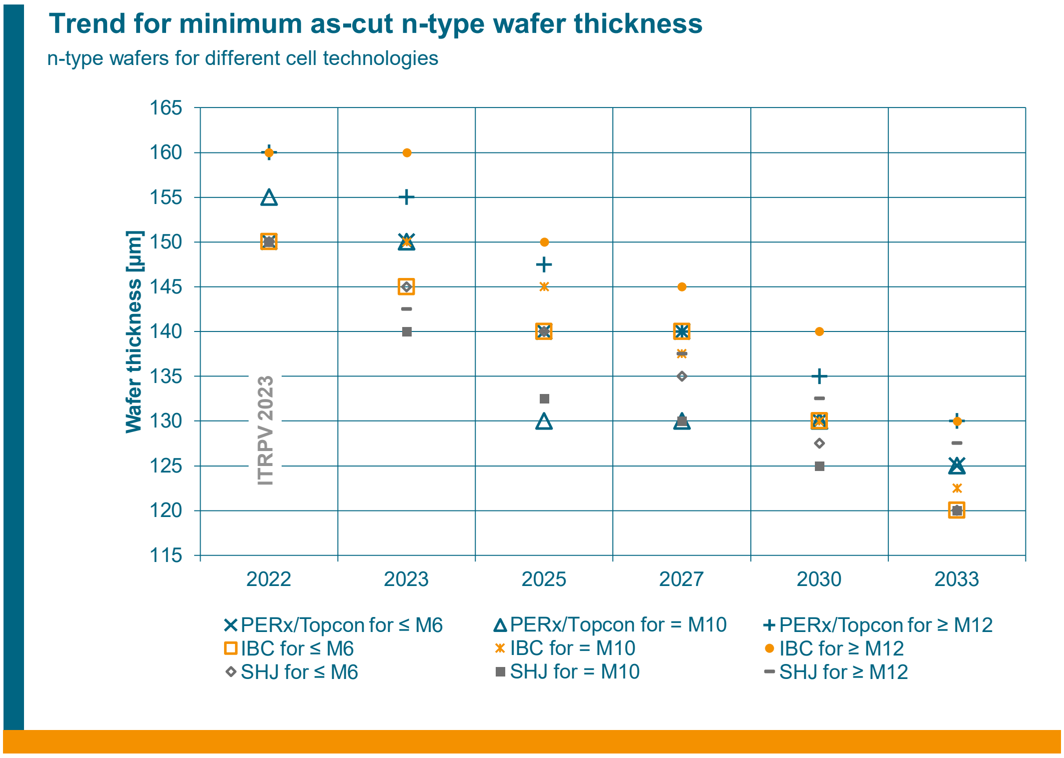


Fig. 8: Predicted trend for minimum as-cut wafer thickness n-type c-Si wafers with different wafer sizes.

thickness limit trend in module technology is discussed in chapter 7.

Fig. 8 shows the anticipated trend of as-cut wafer thickness for n-type mono-Si technologies with the corresponding wafer formats. Current wafer thickness for ≤ M6 wafer size is 150 µm with an expected reduction trend to 120 µm for IBC and SHJ wafers. For larger wafers we see a trend similar to p-type wafers: minimum thickness will be between 5 and 10 µm higher for M10 and G12 wafer formats, respectively. In 2023 we expect about 5 to 10 µm lower thickness for all formats compared to the corresponding p-type wafers. Minimum thickness within the next 10 years will reach values around 125 µm. M6 and M10 format will lead the thickness reduction rate.

Fig. 9 shows the expected market trend for different wafer types. Cz-mono-Si is clearly dominating the market. In 2022, Cz-mono-Si materials had a market share of about 97% in comparison to about only 3% for cast-Si materials. The trend of increased Cz-mono-Si market share is in line with the assumptions of previous ITRPV editions. The plotted analysis of S&P Global for 2022 shows, that the ITRPV result is close to it [20]. The mono-Si market splits into n- and p-type. P-type, the current mainstream, is expected to stay dominant at least until 2025. N-type mono-Si market share is expected to grow to 65% within the next 10 years. Casted Si is expected to disappear on the long run.

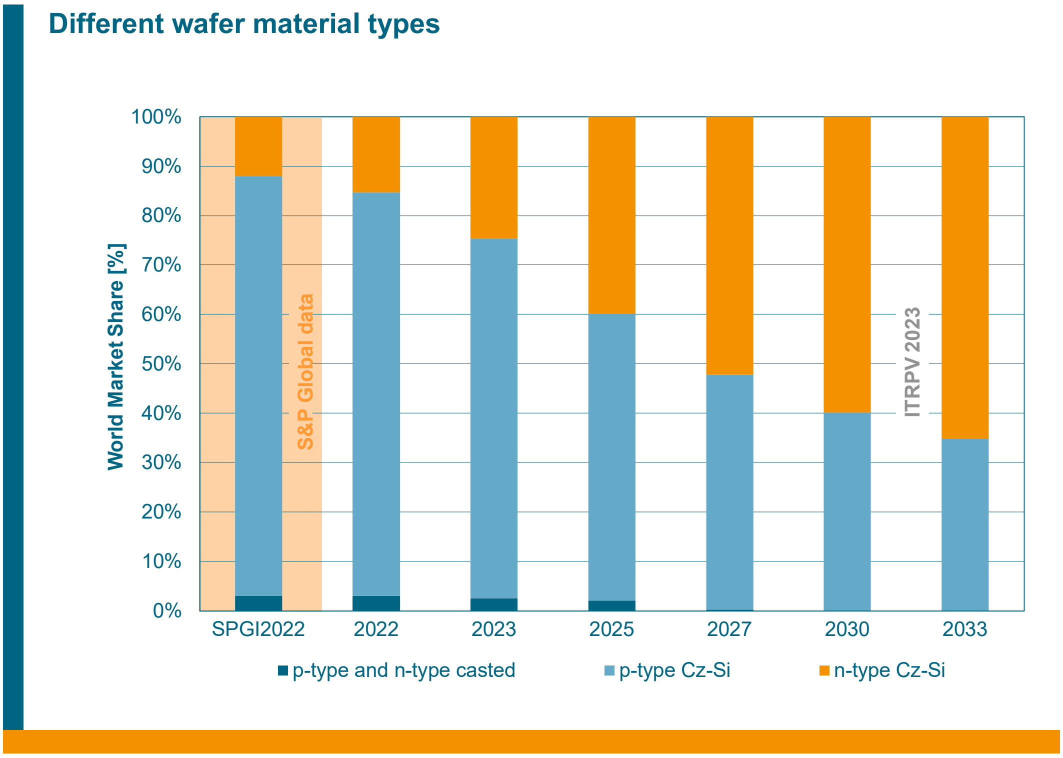


Fig. 9: Market share for different wafer types S&P Global (SPGI) data are indicated for 2022 as reference, [20].

Fig. 10 shows the share of different dimensions for mono wafers. Wafer formats ≤ M6 are losing market share. G1 and M4 are disappearing in 2023. M10 and G12 formats have been dominating the market since 2022 with a higher share of M10 wafer format. It is still not clear yet, which of the two formats will become mainstream in future as both have advantages and disadvantages [21, 22]. So new built cell lines will be ready for both formats and have to be prepared for even >G12 formats.

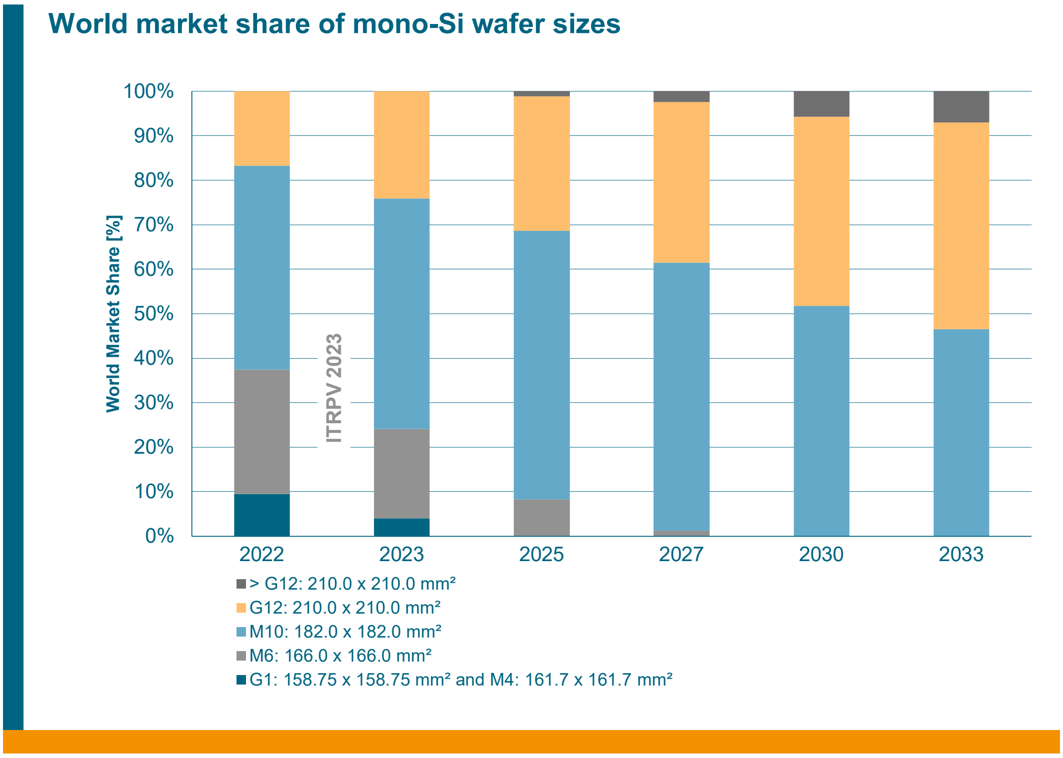


Fig. 10: Expected trend of Cz-mono-Si wafer size in mass production.

A standardization of the different wafer formats is important to enable availability of appropriate production machines and materials like glass and foils for cost efficient manufacturing of modules. SEMI published a specification for Silicon Wafers for Use in Photovoltaic Solar Cells [23] . In addition, there are activities at IEC for a new wafer standard [24]. Also, good news is that M10 based modules have now a standard width of 1134 mm.

6. Result of 2022 | Cell

6.1. Materials

Metallization pastes/inks containing silver (Ag) and aluminum (Al) are the most process-critical and most expensive non-silicon materials used in current c-Si cell technologies. Paste consumption therefore needs to be reduced.

Fig. 11 shows our expectation regarding the future reduction of the silver that remains on 182.0 x 182.0 mm² (M10) cells of different p- and n-type cell concepts after processing. The cell area increase compared to former editions of the ITRPV does not influence the trend but only the absolute value.

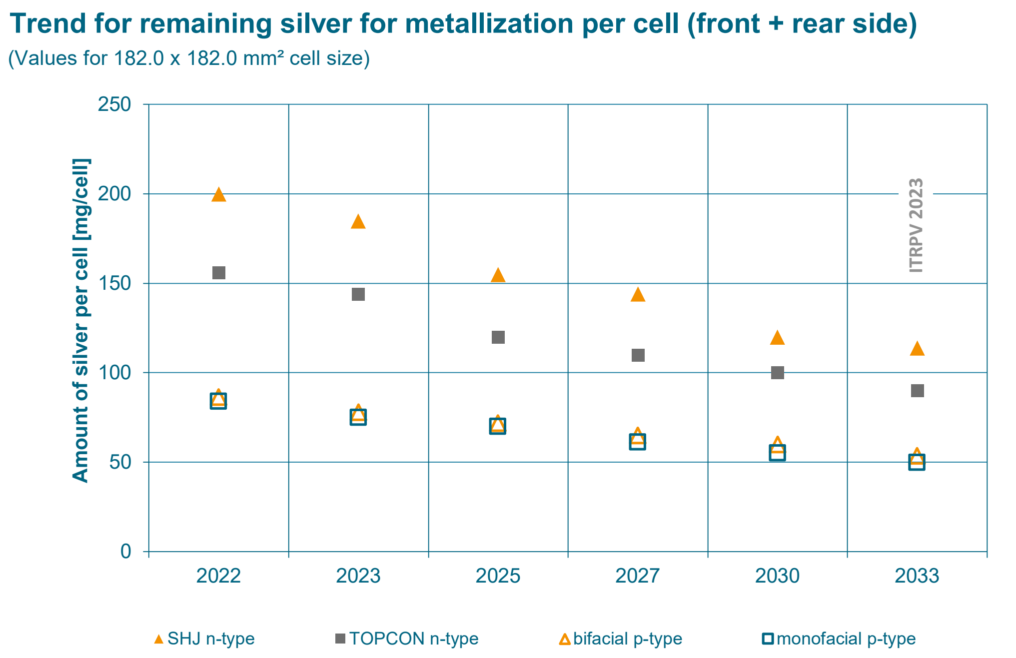


Fig. 11: Trend for remaining silver per cell for different cell concepts in M10 wafer format (182.0 x 182.0 mm²).

To get a better understanding of the Ag consumption, Fig. 12 shows the corresponding average cell level silver consumption per Wp calculated with the expected cell efficiencies according to Fig. 38. Values in mg/Wp are equal to t/GWp.

The reduction of remaining silver per cell will continue during the next years. The current study found about 10 mg/W on cell level as the median value in 2022 standard PERC monofacial and bifacial cells as average of M6, M10, and G12 format. This is ahead of the assumptions in the 13th editions and emphasizes, that silver reduction is continuing. Anyhow, a reduction down to ≈ 6.5 mg/W or ≈ 50 mg per M10 cell is expected to be reached within the next 10 years for PERC. New developments in pastes and screens must enable this reduction, and this points out again the necessity of a close collaboration between suppliers and cell manufacturers to realize this challenge.
The silver price is fluctuating a lot: after 2 years at a quite elevated level of about 800 US$/kg it was in March 2023 at 650 US$/kg [25]. This results in costs of ≈ 0.65 US$ cents/W for a 23.6% mono PERC cell in 2023. Bifacial p-type concepts consume about 5% more silver.

N-type cell concepts show in our survey higher silver consumption than p-type PERC: 80% and 150% for TOPCon and SHJ concepts respectively. This is mainly due to use of silver for front and entire rear side metallization in these concepts. Nevertheless, TOPCon in mass production by Tier 1 manufacturers in China is reported to be end of 2022 on lower consumption levels 2 to 5 years ahead of our prediction [26].

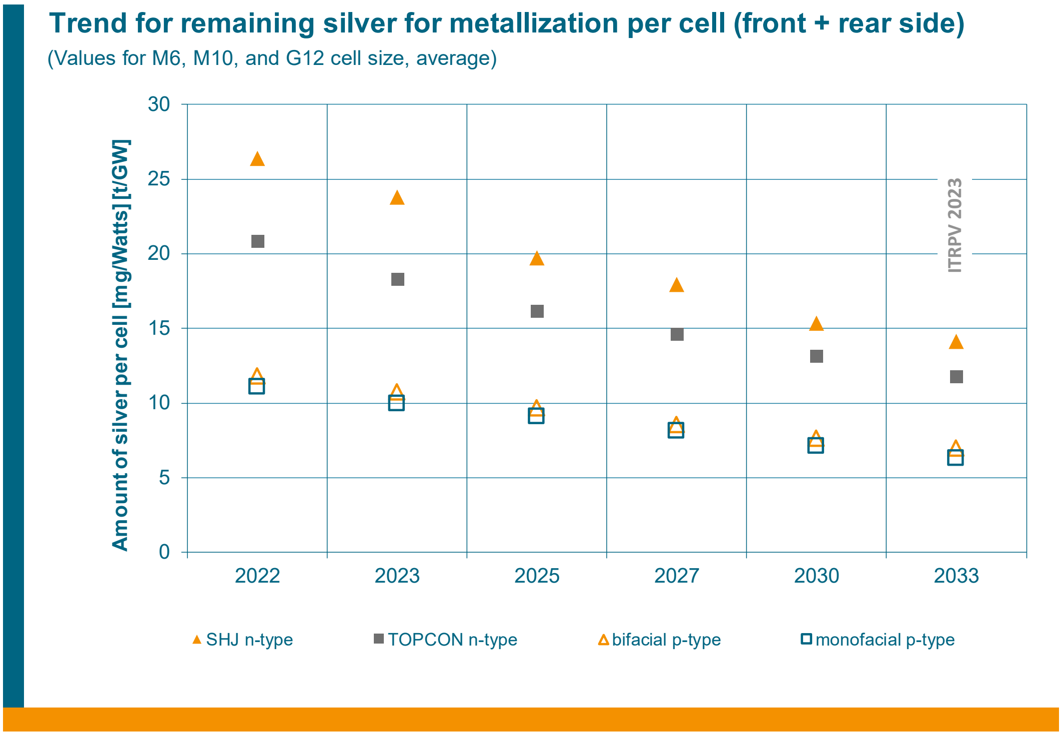


Fig. 12: Trend for remaining silver per cell Wp for different cell concepts as average consumption for M6, M10 and G12 wafer formats and with the cell efficiencies according to Fig.38.

Because silver will remain cost critical due to the world market dependency, it is extremely important to continue all efforts to lower silver consumption as a means of achieving further cost reductions. 300 GW PERC cells in 2022 consumed about 3300 tons of silver, assuming 11 mg/W for 23.2% PERC average production level in 2022. This corresponds to about 10% of world silver supply in 2022 and is within the assumptions of the World Silver Survey 2022 [27]. For full production capacity in TOPCon or SHJ technologies this amount would double as shown in Fig 12. Assuming the current consumption values of [26], TOPCon does not consume much more than PERC. Anyhow, the continued reduction in silver consumption is essential to meet future production and cost targets for c-Si PV.

On top of a continuous reduction of silver consumption at the cell manufacturing level, silver replacement is still considered. Copper (Cu), as less expensive material, applied with plating technologies, is the envisioned substitute, today in use for high efficiency back contact cell concepts. It is still assumed that it will be introduced in mass production, but the market share is considered as conservative as in the last editions with about 7.5% in 2033 according to Fig. 28. No fast increase in market share is expected in copper metallization, based on our results. Technical issues related to reliability and adhesion must be resolved before alternative metallization techniques can be introduced. Appropriate equipment and processes also need to be made ready for mass production. Silver is expected to remain the most widely used front metallization material for c-Si cells in the years to come.

The trend of remaining aluminum is shown in Fig. 13. We distinguish in this figure between bifacial and monofacial PERC technologies. Bifacial cells need much less rear-side aluminum as the rear side grid pattern requires only ≈ 25% of the corresponding monofacial cell full-side aluminum metallization. The reduction for the M10 format over the next ten years is assumed to reach down to 750 mg for monofacial and 200 mg for bifacial cell concepts, respectively.

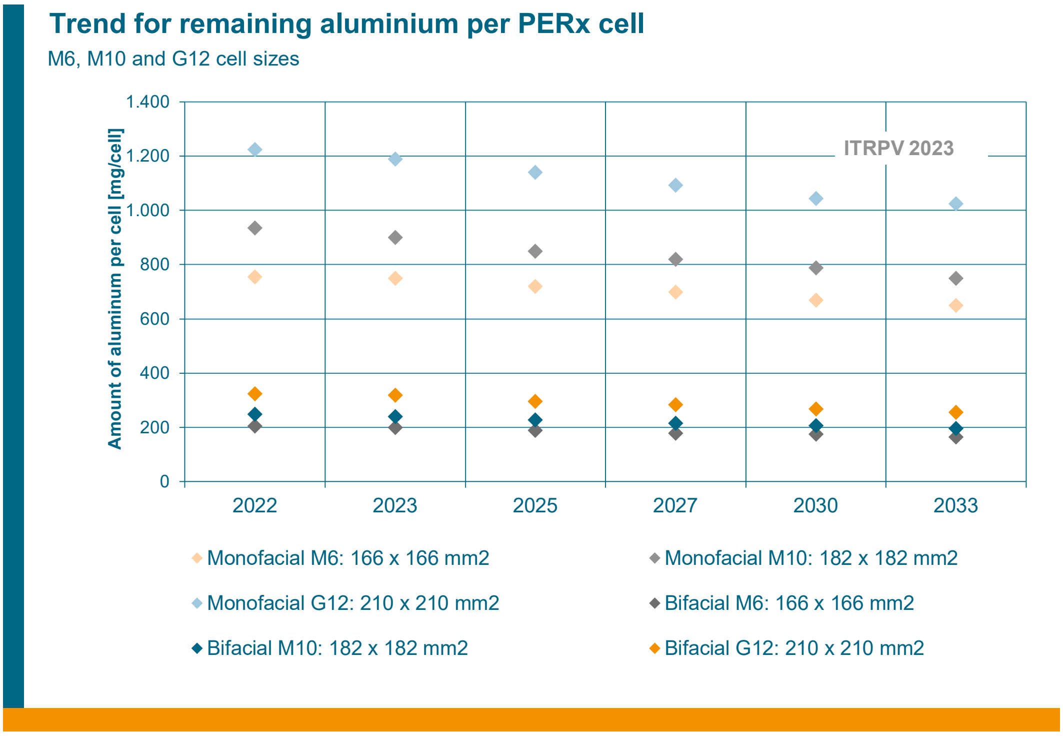


Fig. 13: Trend for remaining aluminum per cell for monofacial and bifacial PERC concepts and for different cell formats.

SHJ cells already use lead free pastes. We see lead free pastes to become more used in the mass production of non SHJ c-Si cells as well.

6.2. Processes

The first production process in cell manufacturing is texturing. Reducing the reflectivity is mandatory to optimize cell efficiency. Mono-Si cell texturing is done with alkaline etching using KOH with additives. This technology is reliable, and throughput optimized with batch processing tools. Only about 1% of mono-Si texturing is assumed to apply Reactive Ion Etching (RIE).

Solar cell recombination losses on the front and rear sides of the cell, as well as recombination losses in the c-Si bulk material, must be reduced in line with high-efficiency cell concepts. The recombination currents J0bulk, J0front, J0rear, indicating the recombination losses in the volume, on the cell's front and rear side respectively, are a reasonable way to describe recombination losses. Fig. 14 and Fig. 15 show the expected recombination current trends for p-type and n-type materials, respectively. The values are in line with the assumptions of former ITRPV editions. Recombination currents can be measured as described in literature [28], or they can be extracted from the I-V-curve if the other J0 components are known. As shown in Fig. 14, the improvement of the p-type mono silicon material quality will continue. J0bulk for mono-Si is expected to reach about 20 fA/cm² within the next 10 years. Reductions of J0bulk will result from further improvements of the crystallization process. J0front and J0rear are expected to improve similar in p-type mono-Si to well below 30 fA/cm² in 2033.

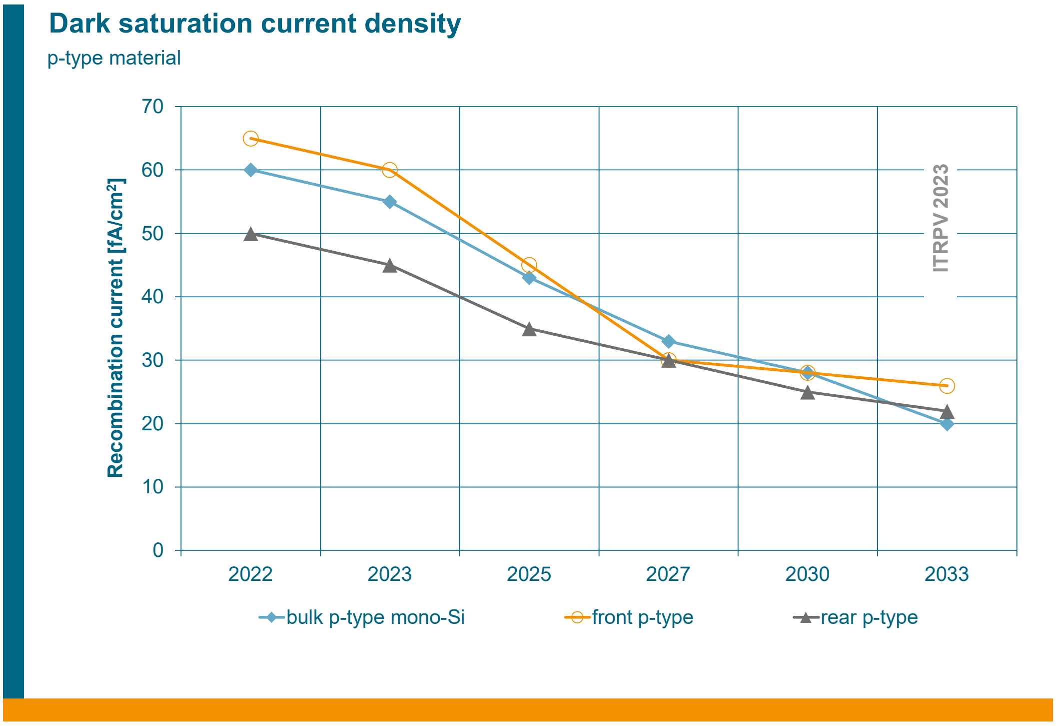


Fig. 14: Predicted trend for recombination currents J0bulk, J0front, J0rear for p-type cell concepts.

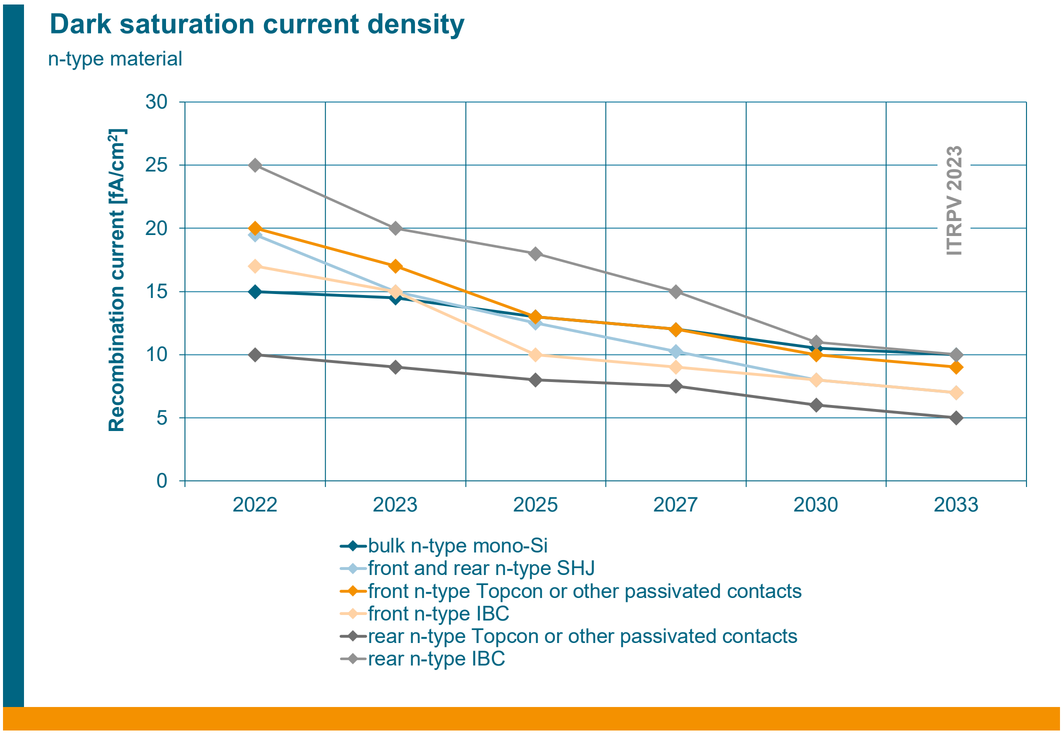


Fig. 15: Predicted trend for recombination currents J0bulk, J0front, J0rear for n-type cell concepts.

Fig. 15 shows that today's n-type mono-Si wafers have J0bulk values below 20 fA/cm², about 30% of the corresponding p-type J0bulk value. J0front and J0rear are also lower for n-type concepts emphasizing the potential for higher cell efficiencies. It is expected that all values will be further reduced to below 10 fA/cm² within the next 10 years. J0rear improvements are linked closely to cell concepts with passivated rear side.

J0front improvements cover all relevant front side parameters (emitter, surface, contacts). A parameter that influences recombination losses on the front surface for cell concepts with diffused pn junctions is the so-called emitter sheet resistance. A high sheet resistance is beneficial for low J0front. Sheet resistances well above 100 Ohm/square can be realized with and without selective emitters. If a selective emitter is used, sheet resistance values refer only to the lower doped region.

Phosphorous is used as dopant to form the pn junction in p-type cell concepts. Fig. 16 shows the current situation for homogenous and selective phosphorous doping: today's sheet resistance of homogenous doped p-type emitters is > 120 Ohm/square and it is expected to increase to 150 Ohm / square. Selective doping allows higher sheet resistances: 150 Ohm/square were standard in 2022. An increase to ≈ 200 Ohm/square is expected within the next years.

Fig. 17 shows the expected market share of different technologies for phosphorous doping in p-type cell processing. Homogeneous gas phase diffusion is a mature, cost-efficient doping technology but high sheet resistances are challenging to contact for highest cell efficiencies. Selective emitter processes resolved this limitation. Applied after standard POCl3 gas phase diffusion, laser based selective emitter processes enable the contacting of lowest phosphorous concentrations with standard metallization pastes. Therefore, selective emitter diffusion techniques are mainstream with a market share of 90% in 2023 and will dominate the future. Laser doped selective emitters are the technology of choice.

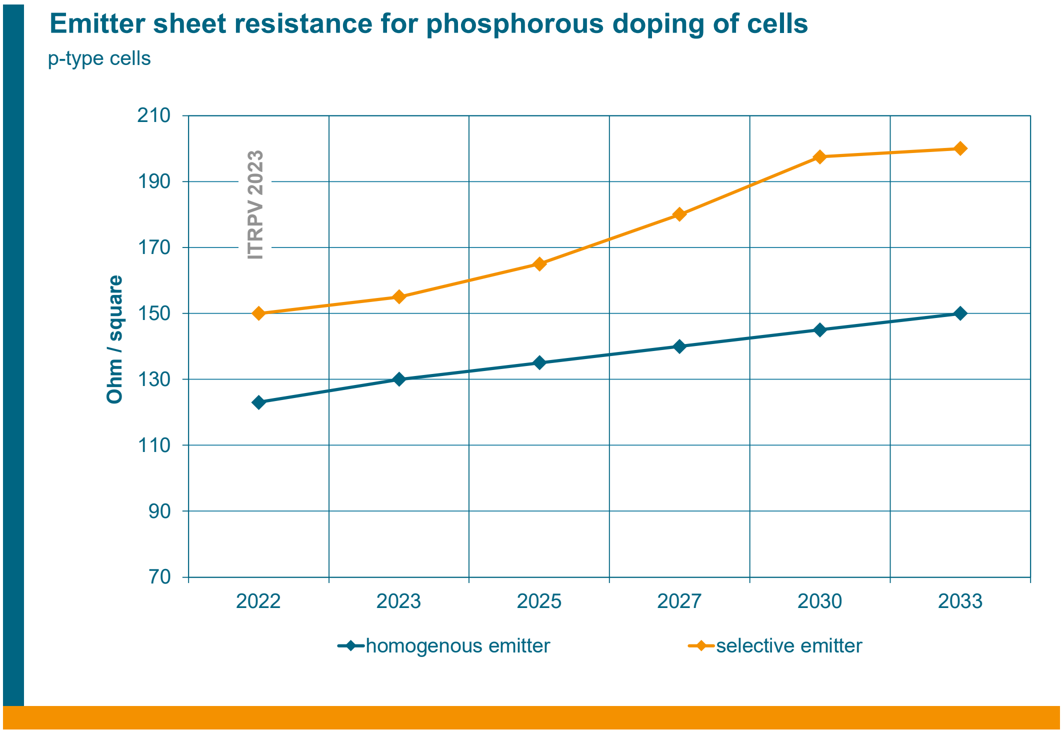


Fig. 16: Expected trend for emitter sheet resistance of phosporous doped emitters for p-type cell concepts. In case of selective emitter the sheet resistance value refers only to the lower doped region.

Different phosphorous emitter technologies for p-type cells

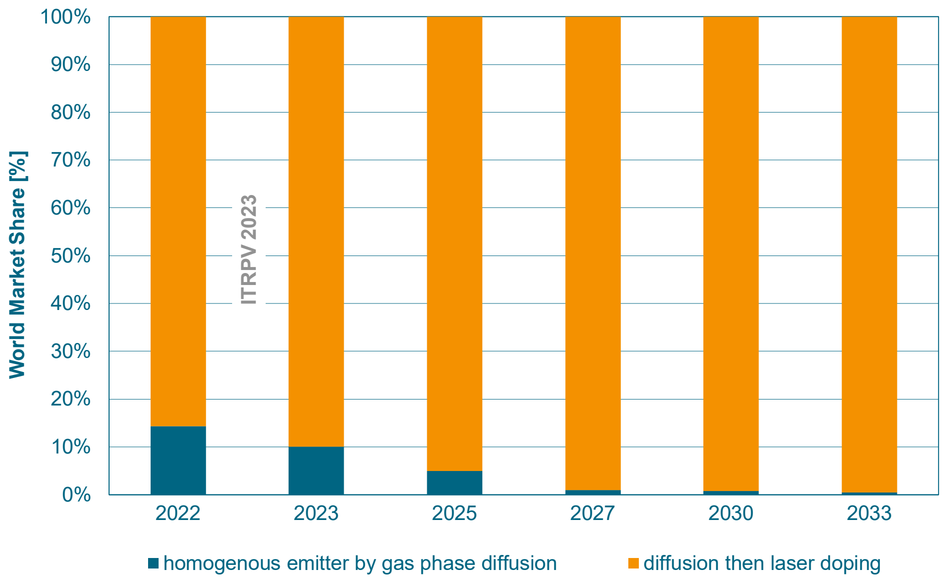


Fig. 17: Expected market share for different phosphorous emitter diffusion technologies for p-type cells.

Boron is the dopant to form the pn junction in n-type diffused cell concepts. The predicted trend for n-type emitters is shown in Fig. 18. For Boron diffusion we also distinguish between homogenous and selective doping. An emitter sheet resistance of over 100 Ohm/square is mostly used in 2023's homogenous boron diffused emitters. An increase to above 140 Ohm/square is expected within the next 10 years. Selective emitters show in 2023 145 Ohm/square. This value will increase to 185 Ohm/square until 2033.

Emitter sheet resistance for boron doping of cells

n-type cells

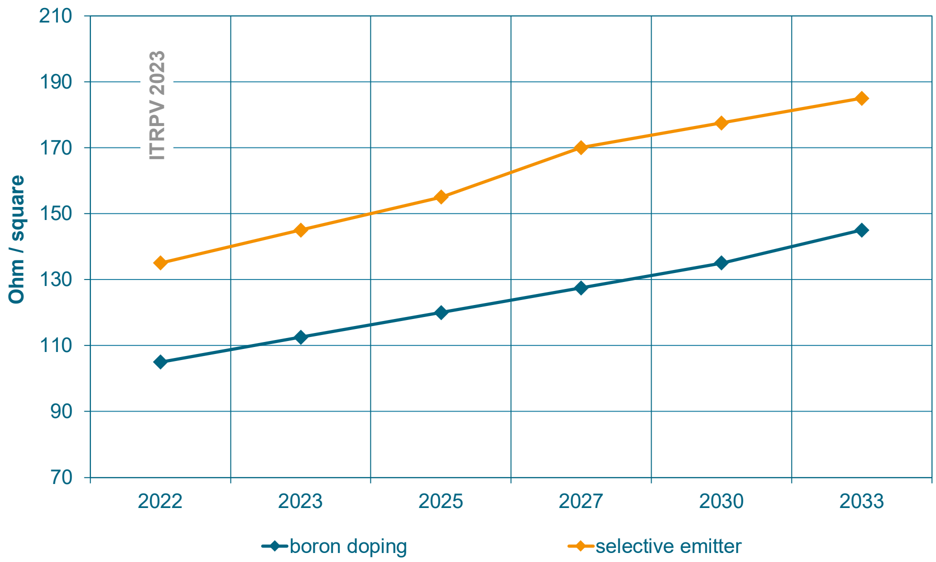


Fig. 18: Expected trend for emitter sheet resistance for boron doping for n-type cell concepts.

Fig. 19 shows the market share of homogenous and selective doping: selective doping will increase the market share from 10% in 2023 to 80% in 2033.

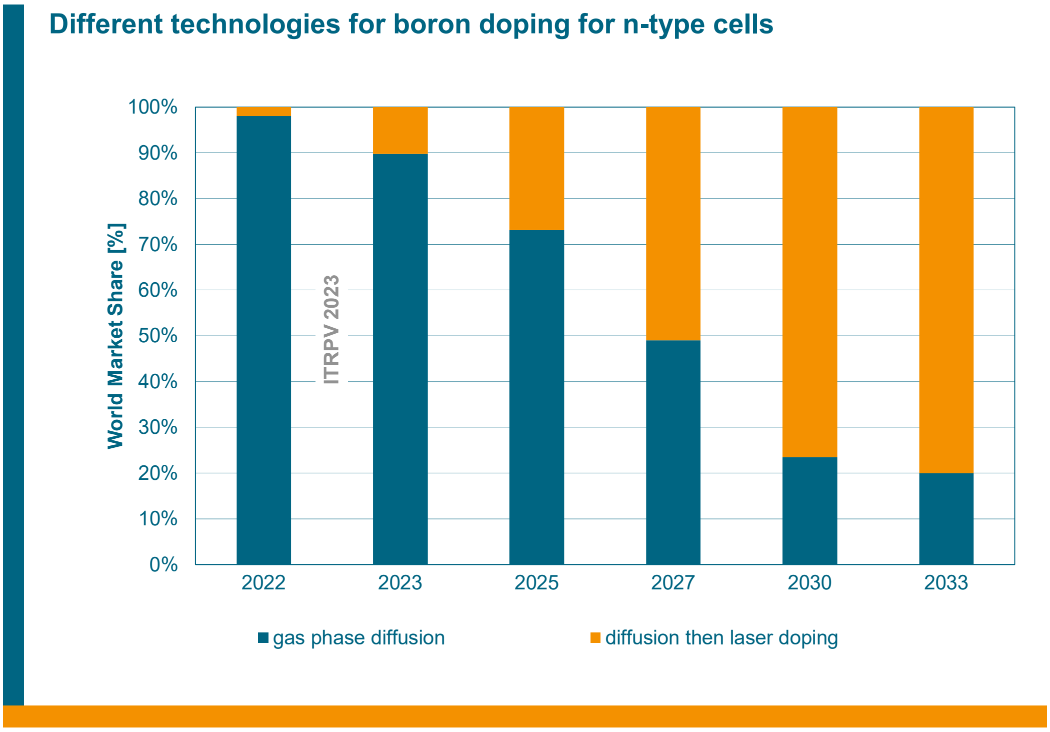


Fig. 19: Expected market share for different technologies for boron doping for n-type cells.

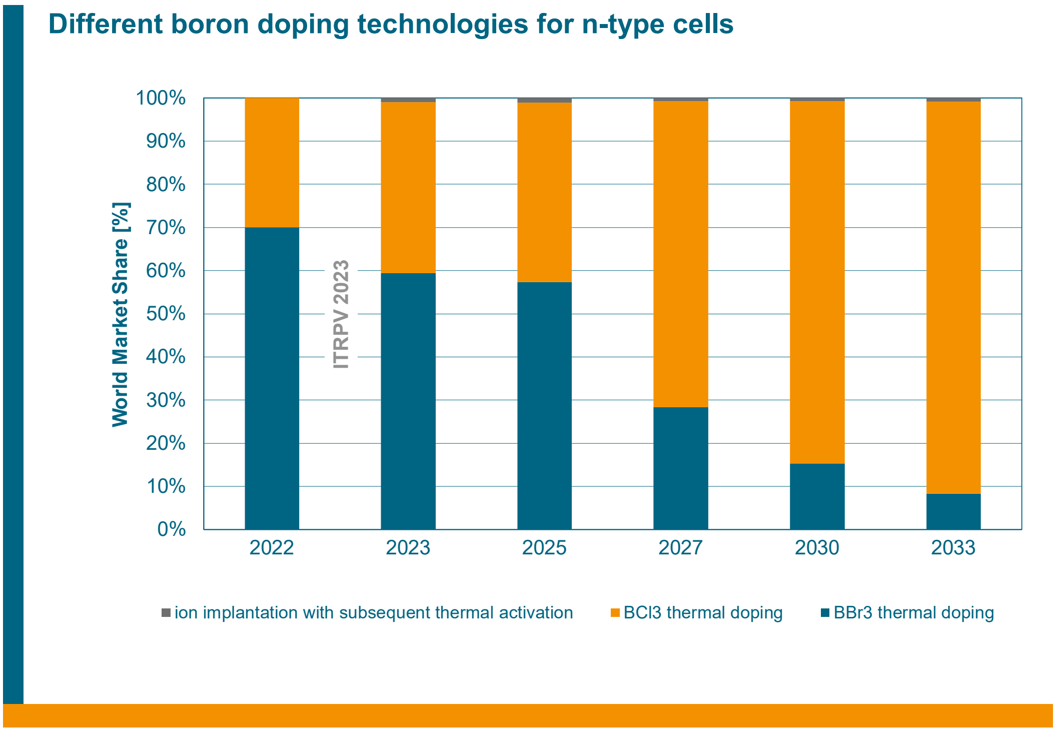
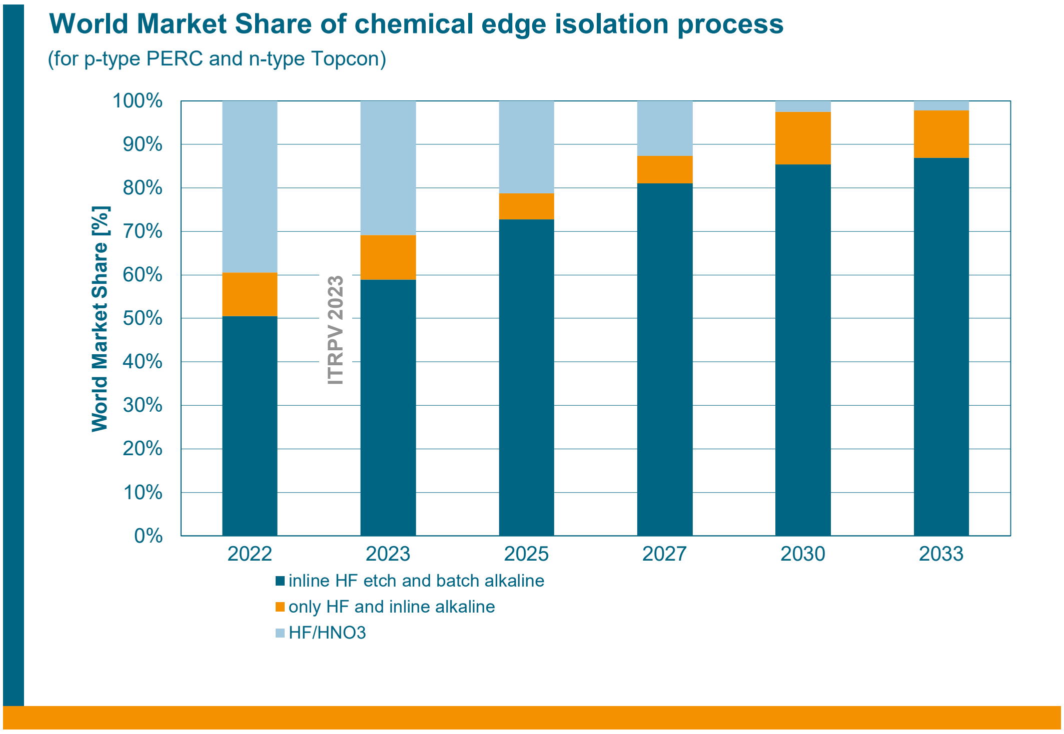


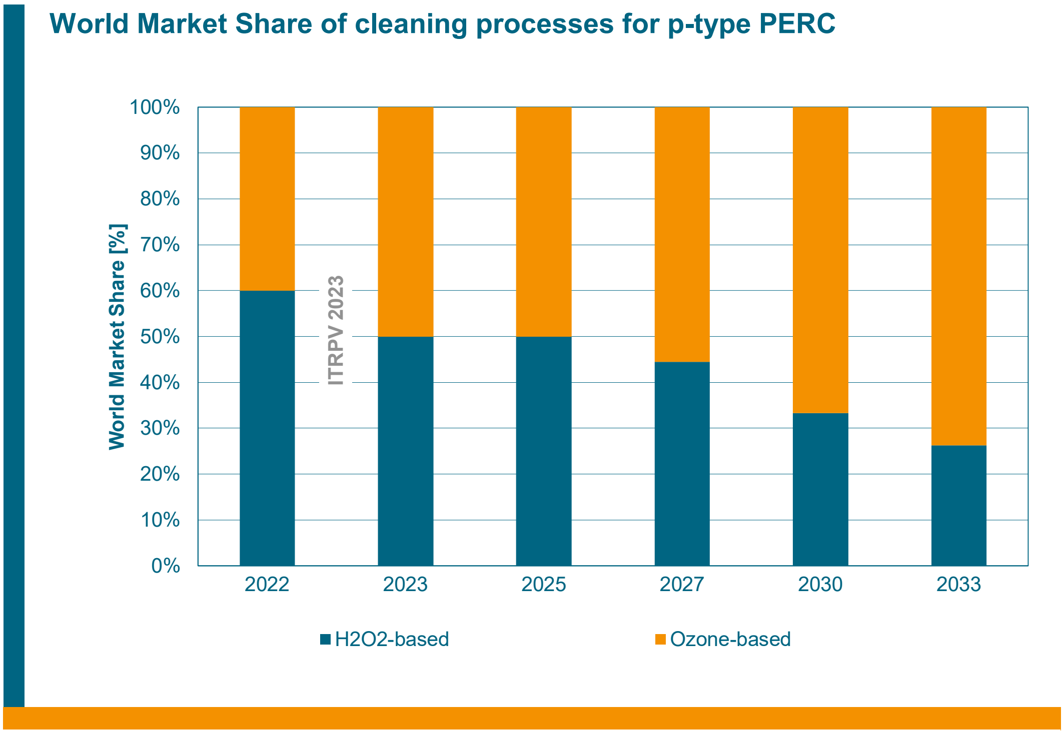
Fig. 20: Expected market share for different technologies for boron doping for n-type cells.

Boron doping for n-type cells in 2023 is to about 60% done with the BBr_3 thermal diffusion technique as shown in Fig. 20. BCl_3 doping is seen the alternative that will become mainstream within the next years. Ion implantation is supposed to stay at low share of < 1%. Alternative processes are not seen with significant market shares so far.

To separate the pn junction from bulk, an edge isolation is required. Wet chemical edge isolation is doing this job in today's manufacturing lines. Fig. 21 shows the market share of the edge isolation process types. In-line processing with HF/HNO_3 has been the mainstream technology in the past. We see that HNO_3 free processing is mainstream from 2023 onwards despite the required combination of in-line HF oxide etching and batch KOH (alkaline) silicon removal. Also we found that there are HNO3



Fig, 21: Market trend of chemical edge isolation process used for isolation of pn junctions in corresponding cell technologies.



Fig, 22: Market trend of cleaning processes for p-type PERC.

free in-line based approaches but with <10% market share. Benefits of KOH based edge isolation are the substitution of expensive HNO_3 and a less expensive process exhaust gas treatment due to the elimination of nitrous fume.

Cleaning processes are mandatory for high efficiency cell production lines. H2O2 based cleaning was most used in the past. Fig. 22 shows that Ozone based cleaning processes will become mainstream within the next years.

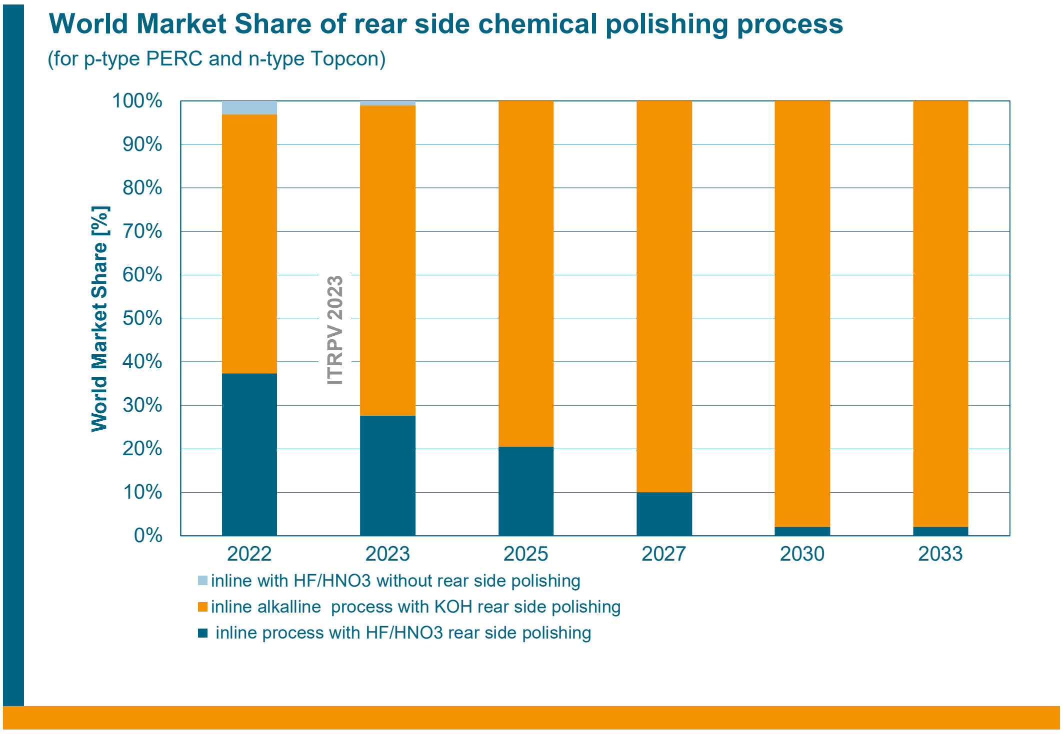


Fig. 23: Expected market trend for required rear side polishing processes.

Beside the edge isolation process also rear side treatment is required. Fig. 23 shows that in-line KOH polishing has been the dominating technology since 2022.

Since 2013, cell concepts using rear side passivation with dielectric layer stacks have been in mass production (PERC/PERT/PERL technology) and are mainstream today in c-Si PV as discussed in 6.3. PERC on p-type has been using aluminum oxide (AlO_x) as rear side passivation layer since the beginning. Fig. 24 shows the expected market shares of different technologies for the deposition of AlO_x passivation layers on the rear side of p-type PERC cell concepts. The market share of remote plasma PECVD Al_2O_3 in combination with a capping layer will continuously shrink within the next 10 years to below 10%. This former mainstream technology for PERC cell concepts is about to be phased out. New built cell production capacities will use direct plasma PECVD Al_2O_3 with integrated capping layer deposition or ALD based Al_2O_3 deposition techniques in combination with separate capping layer deposition.

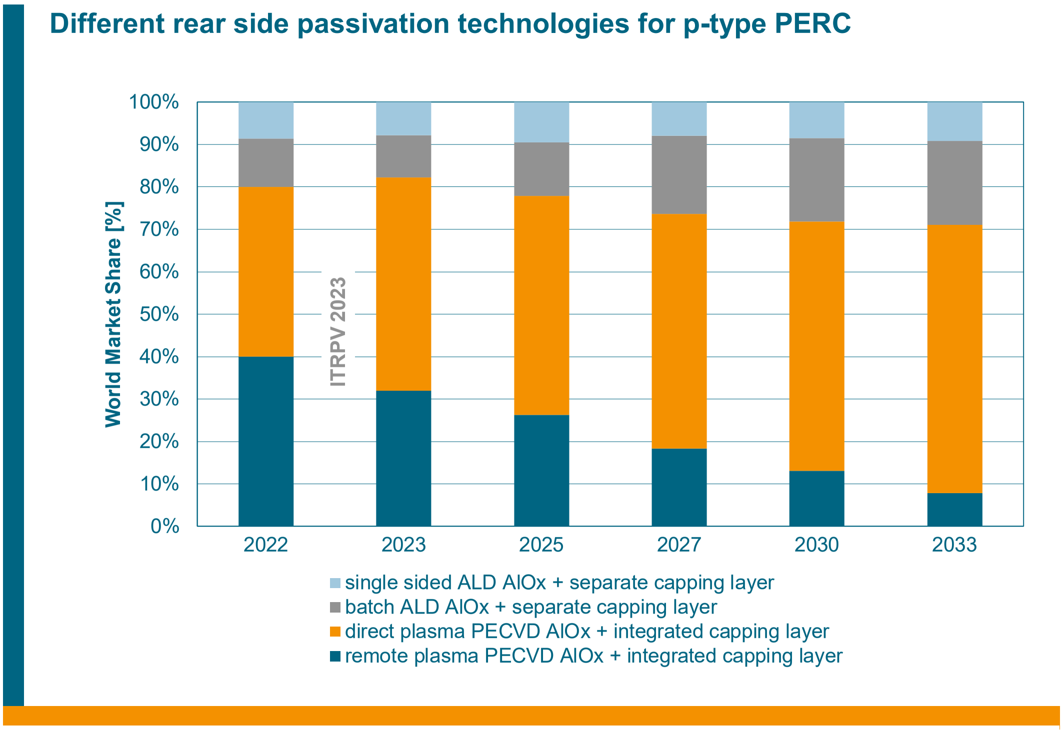


Fig. 24: Predicted market share of technologies for AlOx-based passivation layers for the rear side of p-type PERC.

The marker shares of front side passivation technologies for n-type TOPCon (Tunnel Oxide Passivated Contacts) cell concepts is plotted in Fig.25. The trend is similar to Fig 24: remote plasma PECVD Al2O3

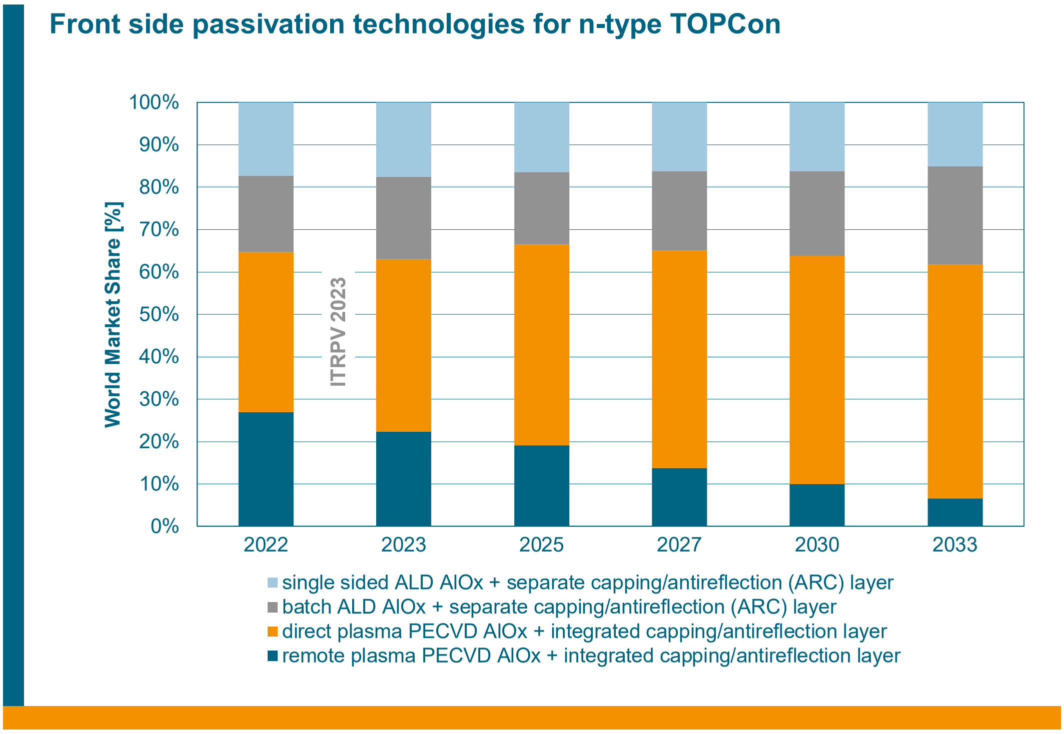


Fig. 25: Predicted market share of technologies for AlOx-based passivation layers for n-type TOPCon cell concepts.

in combination with a capping layer is about to be phased out. Direct plasma PECVD Al2O3 with integrated capping layer deposition or ALD based Al2O3 deposition techniques in combination with separate capping layer deposition are dominating technologies.

Forming electrical contact via tunneling of electrons instead of forming ohmic contacts to the bulk silicon is used for rear side contacting in TOPCon cell concepts. This technique further reduces the forming of recombination centers at the interface and eliminates recombination current losses at resistive bulk contact.

Tunnel oxide formation can be done in an individual process step or in in situ with another process. In situ formation of tunneling oxide in combination with another process is mainstream in TOPCon manufacturing.

The forming of the poly-Si layer is done either by LPCVD, or by PECVD. Fig. 26 indicates that LPCVD, dominating in 2023 with about 70% market share will be replaced within the next years by PECVD. PECVD market share in 2033 will be at least 80%.

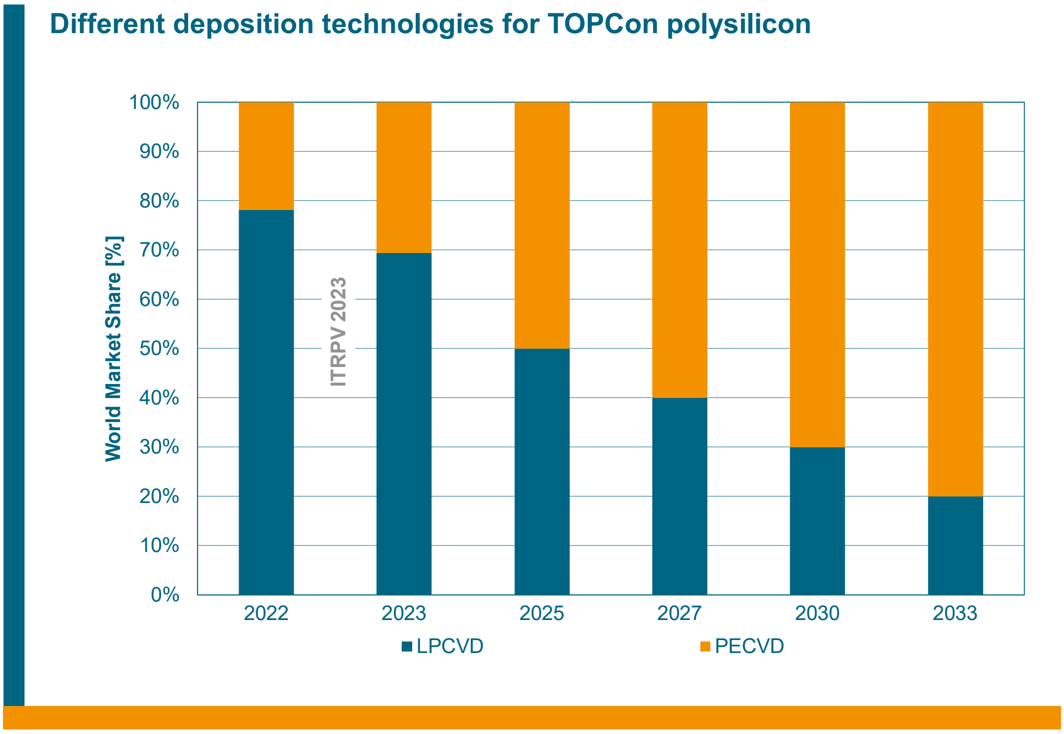


Fig. 26: Expected trend of forming the polysilicon layer of TOPCon contacts.

PECVD poly-Si deposition enables in situ doping of the deposited poly silicon. Therefore, in situ doping will dominate in the market over ex-situ doping that requires additional equipment.

Fig. 27 shows the anticipated thickness trend of the poly-Si layer deposited for TOPCon concepts. The 110 nm in 2023 will be reduced to below 70 nm.

Contacting the emitter and the rear side of the solar cell is the final processing sequence in solar cell manufacturing and a key process regarding cost, efficiency, and quality.

Screen printing has been the technology of choice for front and rear side metallization since the beginning of c-Si solar cell mass production. We see screen printing also in the future as the mainstream metallization technology as shown in Fig. 28. Plating is still considered to be deployed as front side metallization technology with market shares above 5% after 2026 onwards. Other technologies are so far not reported to be in the mass manufacturing market.

Three different approaches for high quality front side print exist. Fig. 29 summarizes the available technologies and their estimated market share during the next 10 years. New front side metallization pastes enable the contacting of the previously discussed low doped emitters without any significant reduction in printing process quality.

Dual printing is mainstream today and will squeeze out single print until 2023. Double printing with a small market share of about 8% in 2023 is expected to disappear within ten years. Dual und double print require an additional printing step with fine-alignment capabilities.

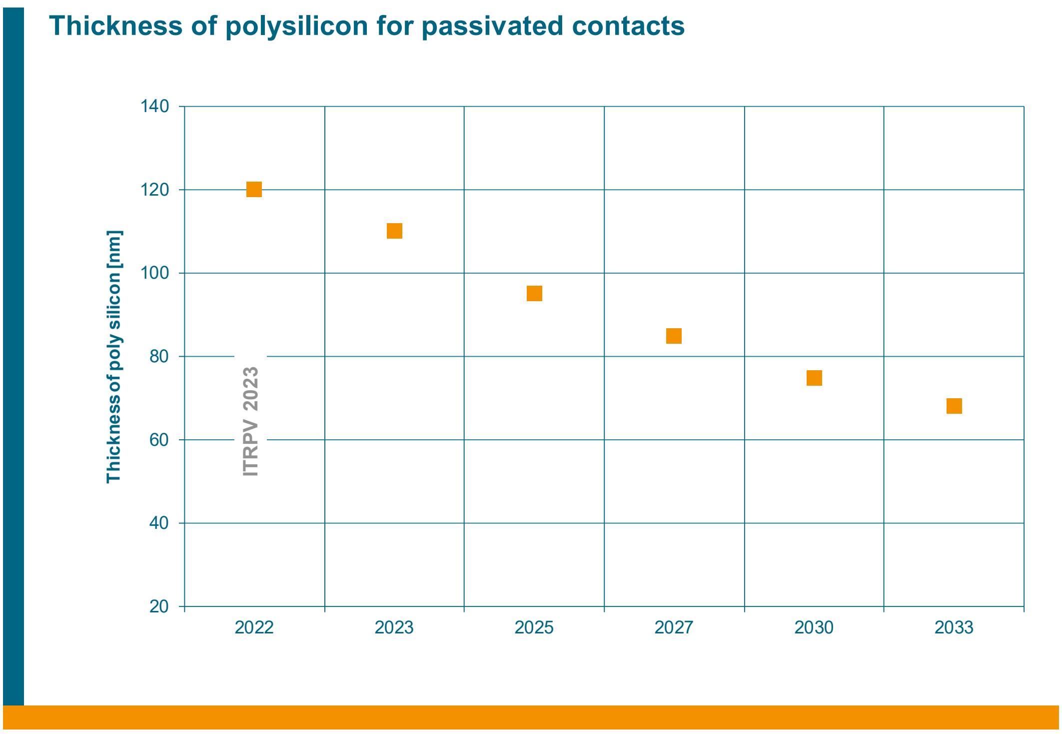


Fig. 27: Expected trend of polysilicon thickness for TOPCon layer stack formation.

A reduction in finger width is one method yielding efficiency gain and cost reduction, but only if it is realized without significantly increasing finger resistance. Furthermore, contact with a shallow emitter needs to be established reliably. One possible way to achieve these goals is to use selective emitter technologies as shown in Fig. 16 and Fig. 18, preferably without significantly increasing processing costs.

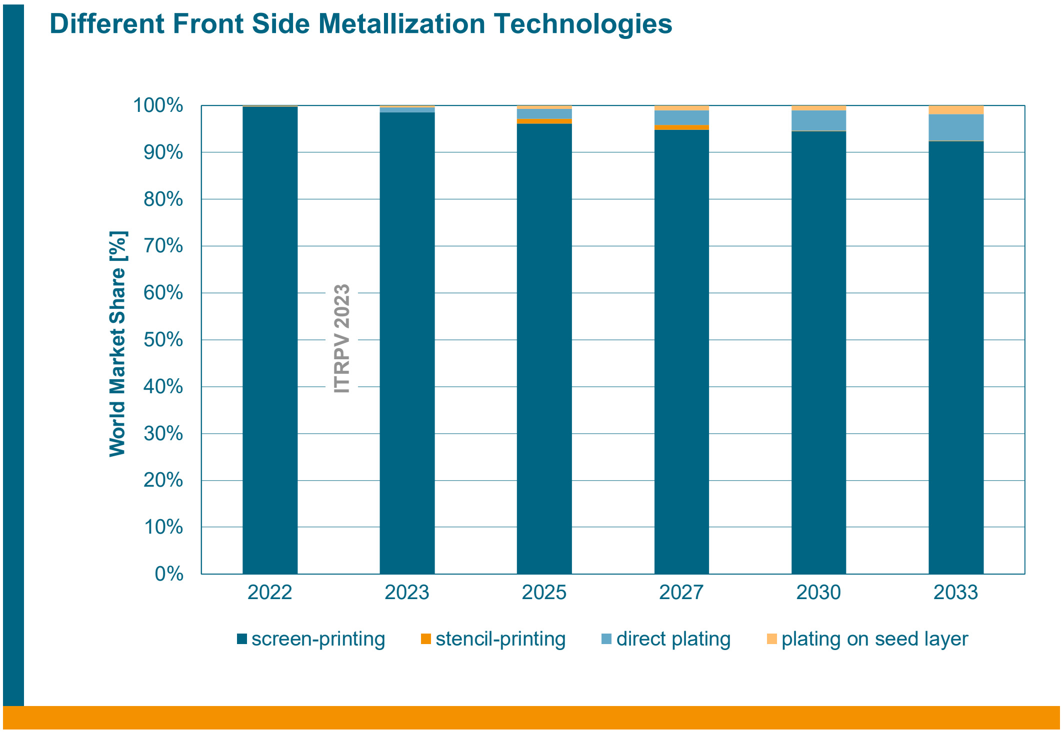


Fig. 28: Expected market share of front side metallization technologies.

Reduction of finger width reduces shadowing. To maintain conductivity a trade-off has to be made, if the roadmap for silver reduction, as discussed in chapter 6.1. will be executed. Finger widths of about 30 µm were standard in 2022 as shown in Fig. 30. A further reduction to 15 µm over the next 10 years is required to meet the silver reduction targets discussed in 6.1.

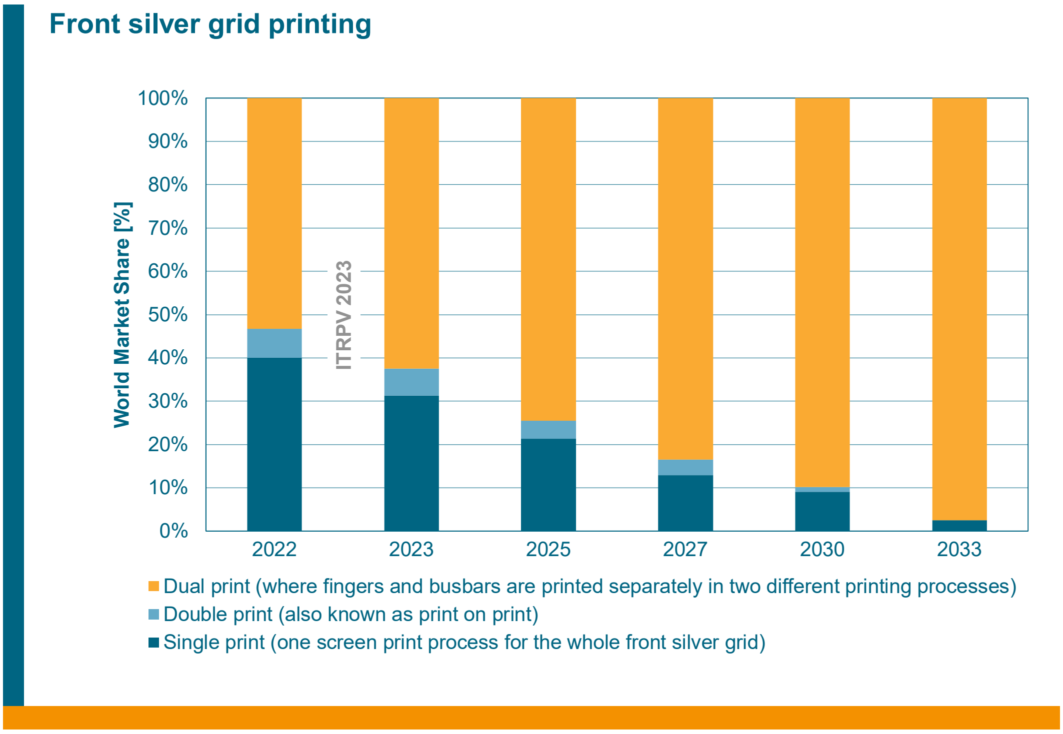


Fig. 29: Expected market share of different front side printing techniques.

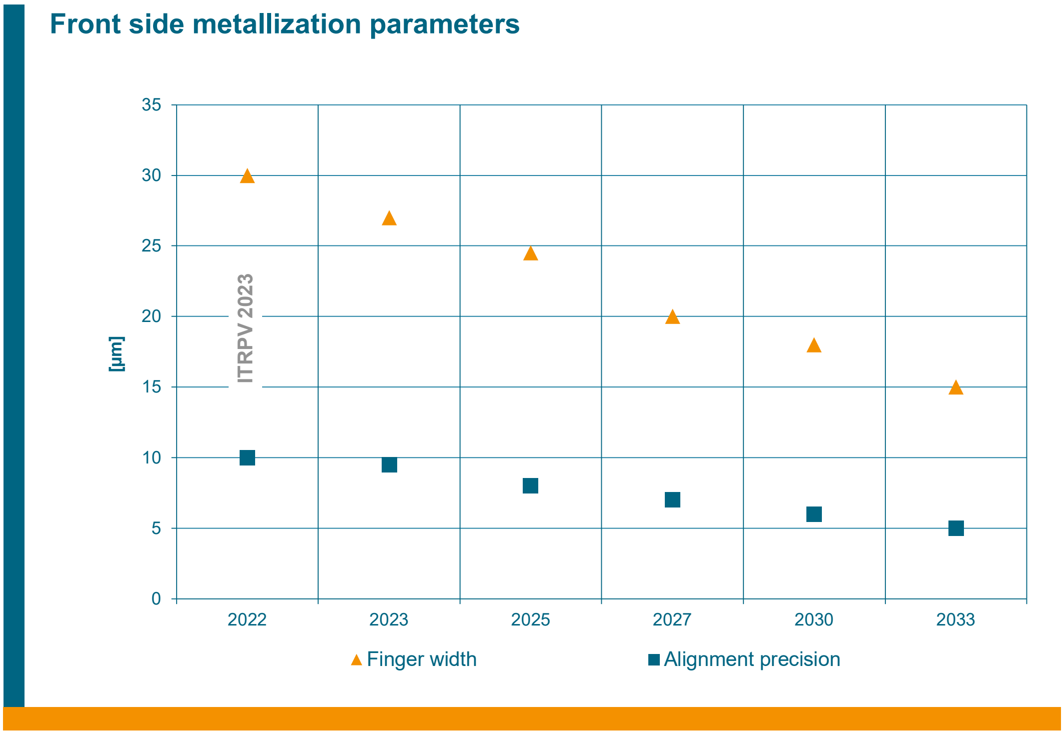


Fig. 30: Predicted trend for finger width and alignment precision in screen-printing. Finger width needs to be reduced without any significant reduction in conductivity.

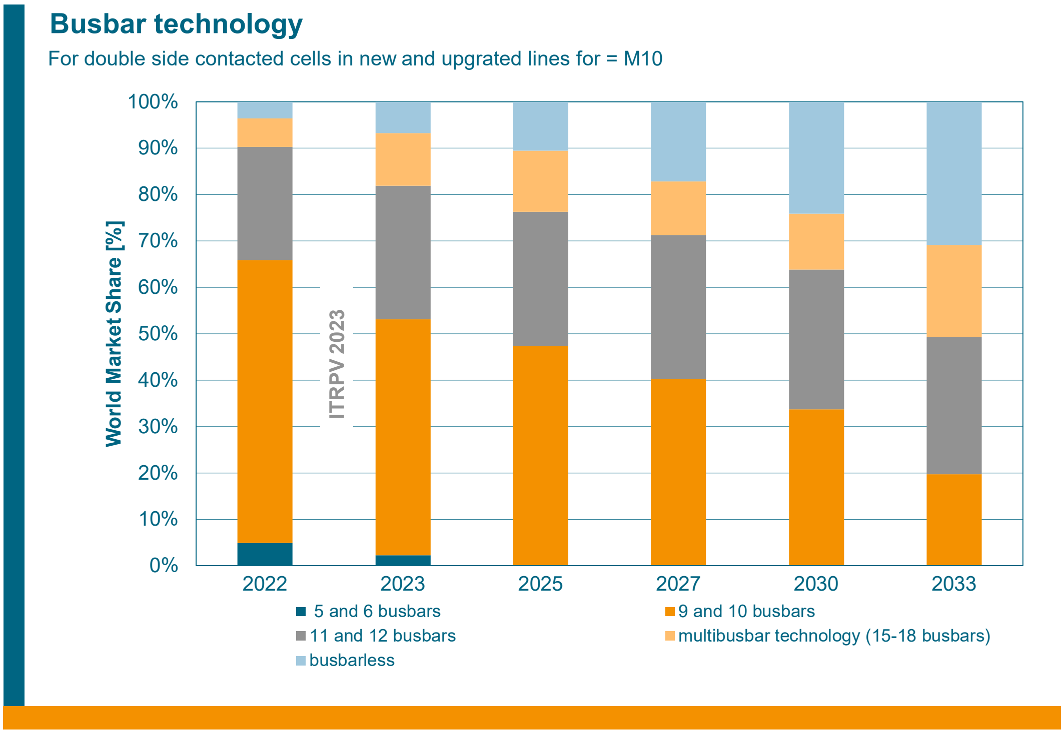


Fig. 31: Market share for different busbar technologies for cells in M10 format.

Besides the reduction of finger width, the printing alignment accuracy requirements are of increasing importance. Dual print separates the fingerprint from the busbar (BB) print, enabling the use of special busbar pastes with less silver but excellent soldering capabilities. Busbarless cell interconnect techniques can even omit the busbars completely. For reliable module interconnection and for bifacial cells, a good alignment accuracy in metallization is also mandatory - an alignment accuracy of down to 5 µm (@+/- 3 sigma) will be required in the future as Fig. 30 shows.

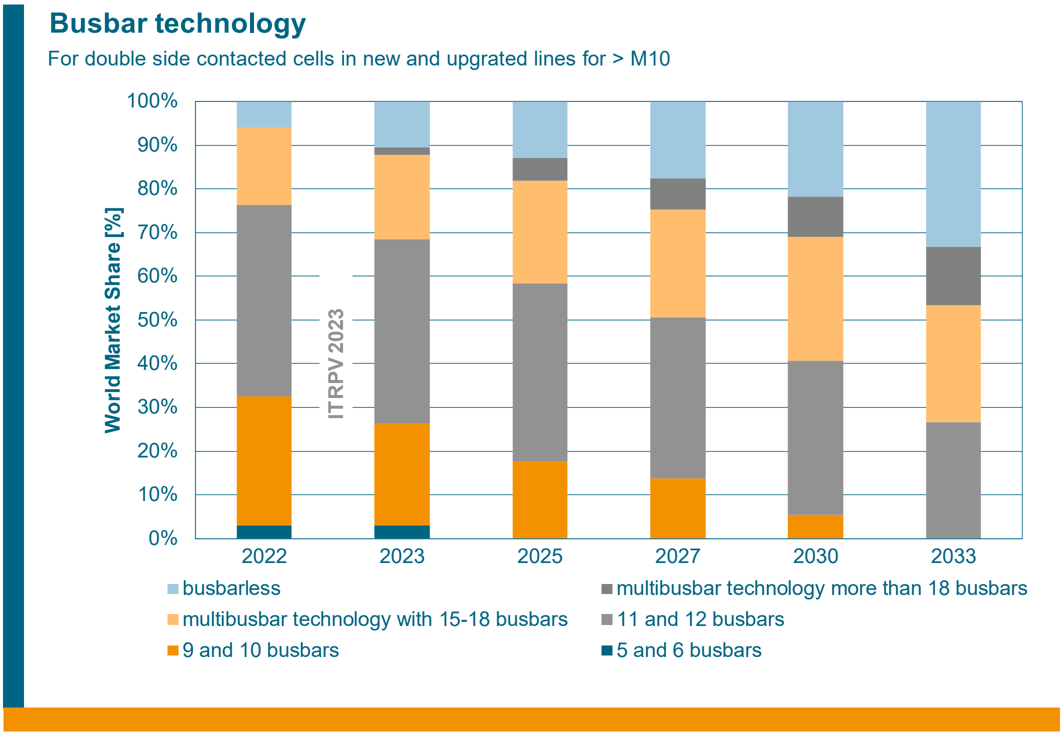


Fig. 32: Market share for different busbar technologies for cells larger than M10 format.

This will be necessary especially regarding an improved alignment to subjacent structures as in the case of selective emitter structures.

Reducing the finger width is going in parallel with increasing the number of busbars. Fig. 31 and Fig. 32 show details on this metallization trend for cells with the format ≥ M10. Layouts with 5 and 6 BBs are disappearing in those formats. Layouts with 9 to 12 BBs are dominating the market. Layouts with >12 BBs and BB-less layouts are expected to gain market share. BB-less technologies support minimum finger widths shown in the Fig. 30 trend. Nevertheless, BB-less layouts will require new interconnection technologies in module manufacturing that - in best case - should be implemented by upgrading of existing stringing tools.

Optimizing productivity is essential to be cost competitive. Increasing the throughput of the equipment in order to achieve maximum output is therefore a suitable way to reduce tool related costs per cell and hence per Wp. To optimize the throughput in a cell production line, both, front-end (chemical and thermal processes) and back-end (metallization and classification) processes should have equal capacity. In former editions of the ITRPV we considered two scenarios: an evolutional optimization approach to optimize existing tool sets and a progressive scenario, for trends of new equipment's, with higher process throughputs. As discussed in chapter 5.3., we currently see that wafer formats ≥ M10 are mainstream. New tools will be capable to process all those formats as well as M6.

In Fig. 33, Fig. 34, and Fig. 35 we summarize the expected throughput trends of new tools capable for processing cell formats ≥ M10.

Fig. 33 shows the expected throughput trend in chemical processing and pure thermal processing: diffusion, oxidation, and annealing. Chemical processing tools are leading the throughput list with about 11,500 wafers/h for 2023 in batch processing (for e.g. texturing). Boron diffusion requires long process times and therefore the throughput is limited to about 4,000 wafers/h in 2023. Throughput for B-diffusion is expected to increase to 7,000 wafers/h within the next 10 years.

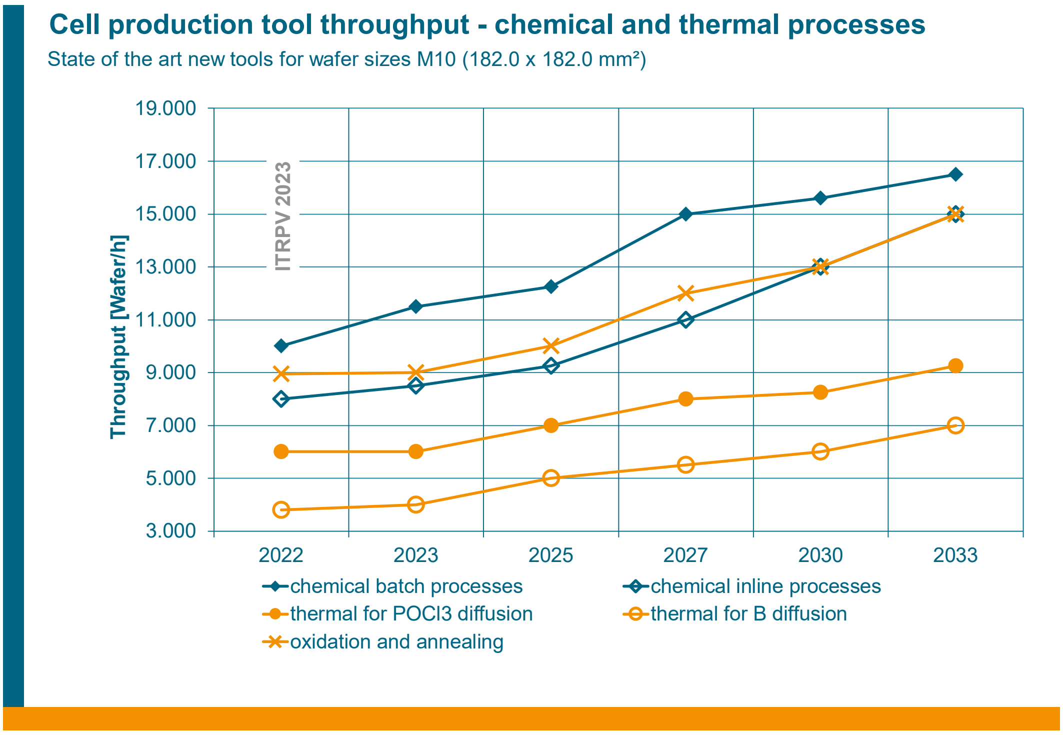


Fig. 33: Predicted trend for throughput per tool of cell production equipment in the frontend.

Fig. 34 shows the expected throughput trends for layer deposition tools. ALD is leading in this process field with 11,000 wafers/h in 2023 and expected 14,000 wafers/h in 2033.

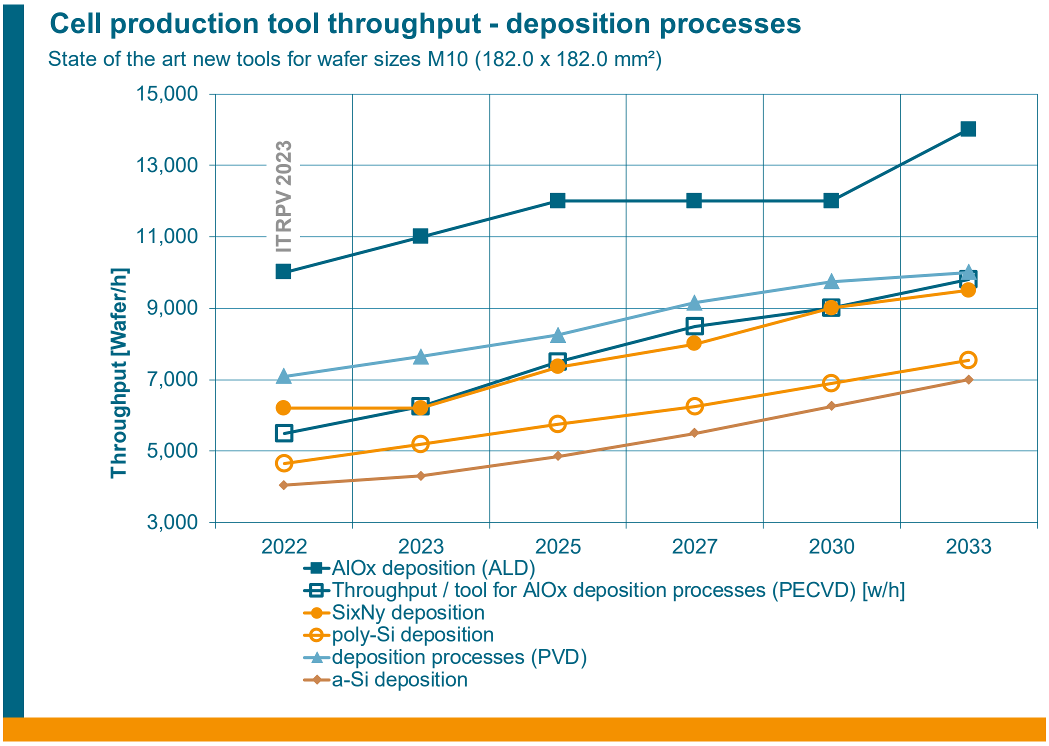


Fig. 34: Predicted trend for throughput per tool of cell production equipment for layer deposition.

The throughput trend in cell processing backend is shown in Fig. 35. Screen printing tools with throughputs of ≈ 7,500 M10 wafers/h are available on the market in 2023. Laser contact opening before printing, as well as firing and testing after screen printing are installed in line in contemporary

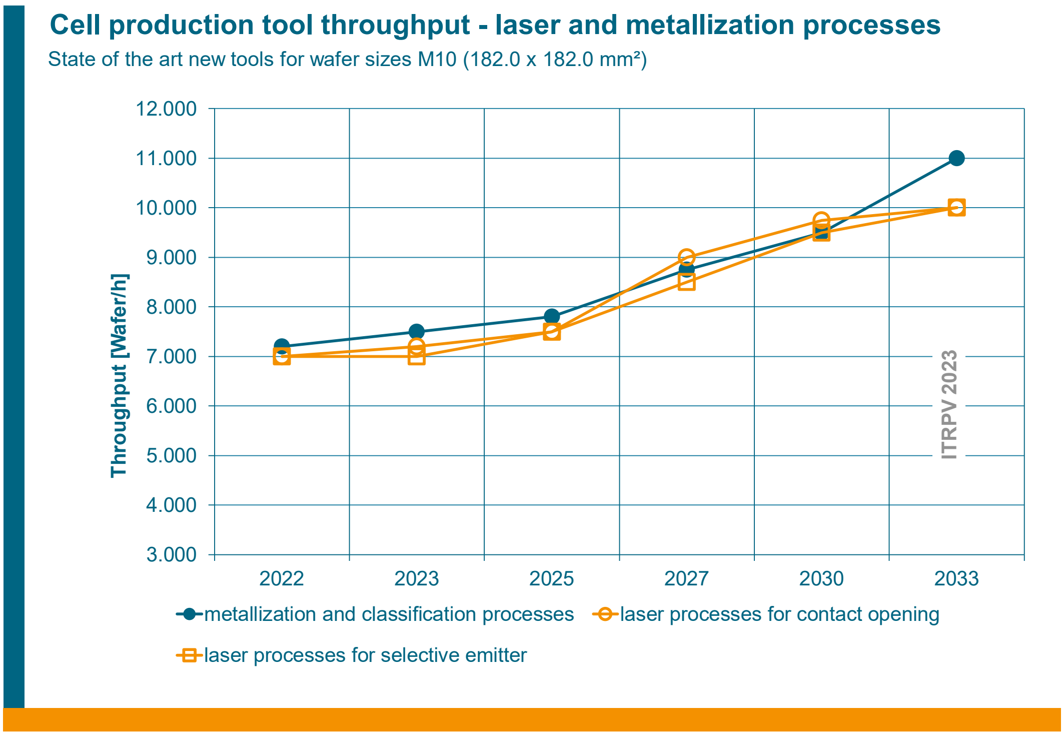


Fig. 35: Predicted trend for throughput per tool of cell production equipment in backend processing.

cell production lines, meeting the same throughput figures. Further improvements in this field will depend strongly on the progress made with the screen-printing technology that currently focuses on narrower line finger width and lower paste consumption.

6.3. Products

The aluminum BSF cell concept is expected to be phased out within 2023. Nevertheless, the matured concept of diffused and passivated pn junctions will be further used in the mainstream with different other rear side passivation technologies (PERC/PERL/PERT/TOPCon). There are different approaches to realize such cells. The most mature approach is the PERC technology, using p-type material with a passivating layer of Al_2O_3 and a SiN_x capping layer as discussed in chapter 6.2. In 2022 the market share of PERC p-type mono-Si was 80% as shown in Fig. 36. The share of p-type mono-Si PERC will decrease to

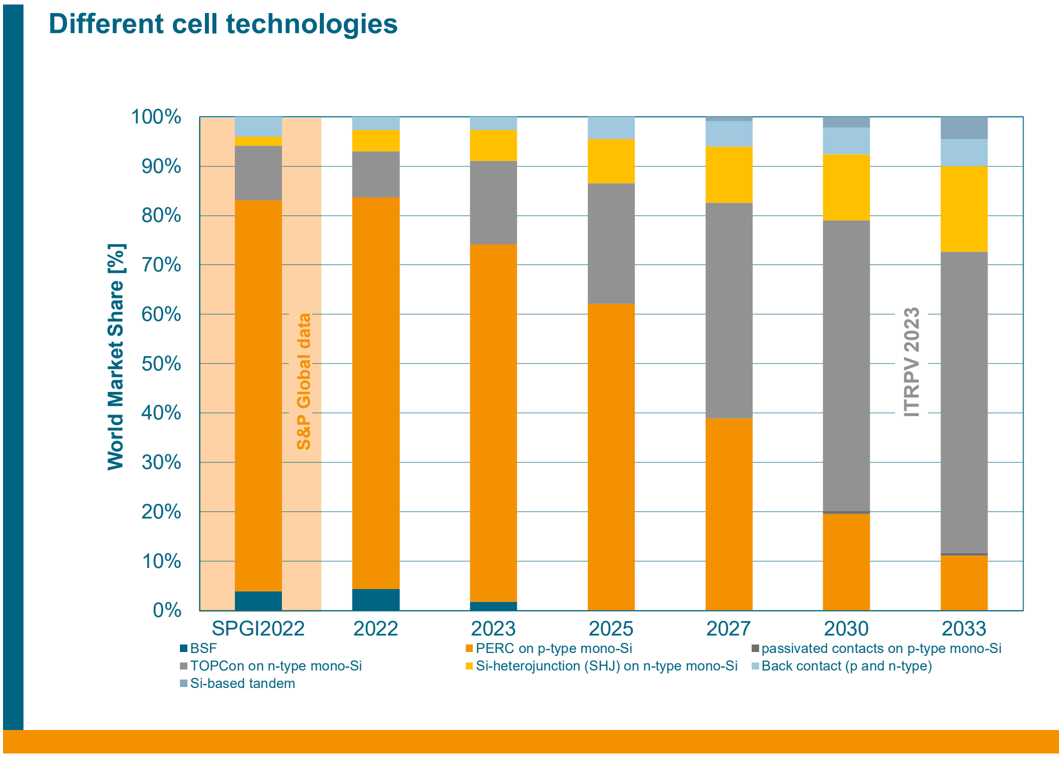


Fig. 36: Market shares for different cell technologies. S&P Global (SPGI) data for 2022 are indicated as reference [20].

about 10% within the next 10 years. Upcoming, promising new cell technologies are using n-type material as shown in Fig. 9. TOPCon on n-material using tunnel oxide passivation stacks at the rear side, will gain market share from about 10% in 2022 up to 60% within the next 10 years. Based on our results, TOPCon on n-type is expected to become the dominating cell concept after 2025.

SHJ cell technology, the second important n-type concept is expected to increase the 2023 market share of about 9% to over 25% within the next ten years. The first pillar in Fig. 36 shows, that our findings for 2022 are in line with the SPGI analysis [20]. Fig. 36 also confirms again the market dominance of double-sided contact cell concepts. Rear-side contact cells are not expected to have significant market share: we assume a change from ≈ 2% in 2022 to about 5% in 10 years. Si-based tandem cells are expected to appear in mass production after 2025, a delay compared to the assumptions in the 12th edition.

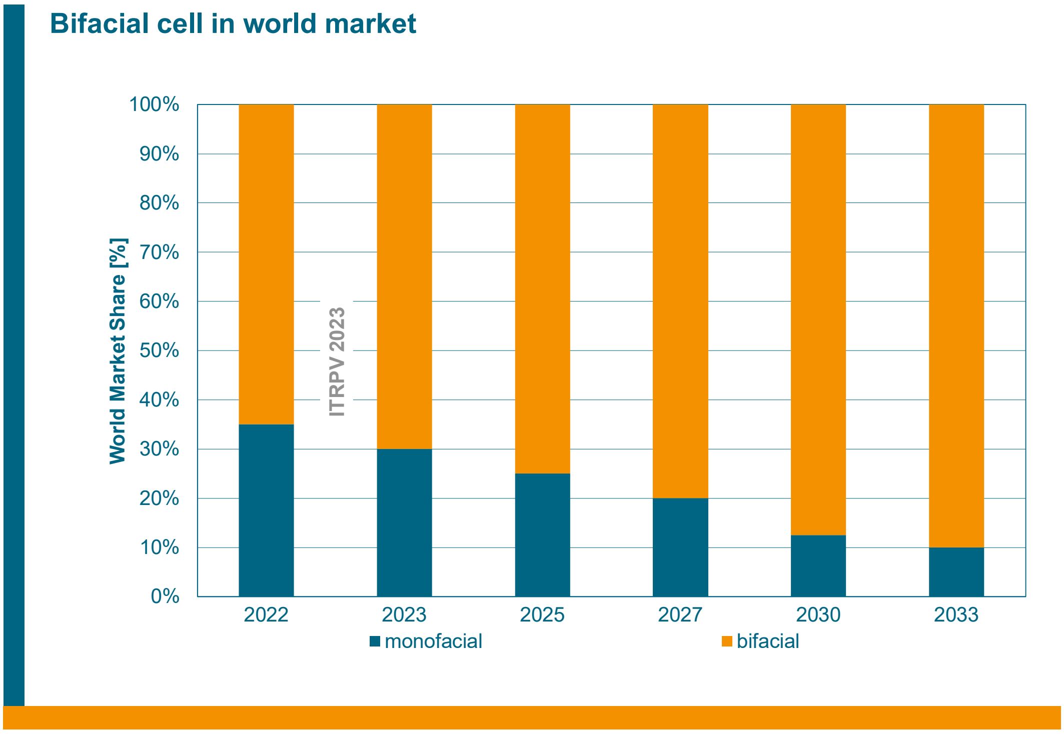


Fig. 37: Market share for bifacial cell technology.

PERC, TOPCon, and SHJ cells can capture the light from the front and from the rear side if the electrical contacts are designed accordingly. These cell types can therefore be perfectly used for bifacial light capturing. Fig. 37 shows the expected market trend for bifacial cells. The market share of 70% in 2023 is expected to increase further to 90% within the next 10 years. Bifacial cells can be used in conventional, monofacial modules or in bifacial modules with transparent rear sides.

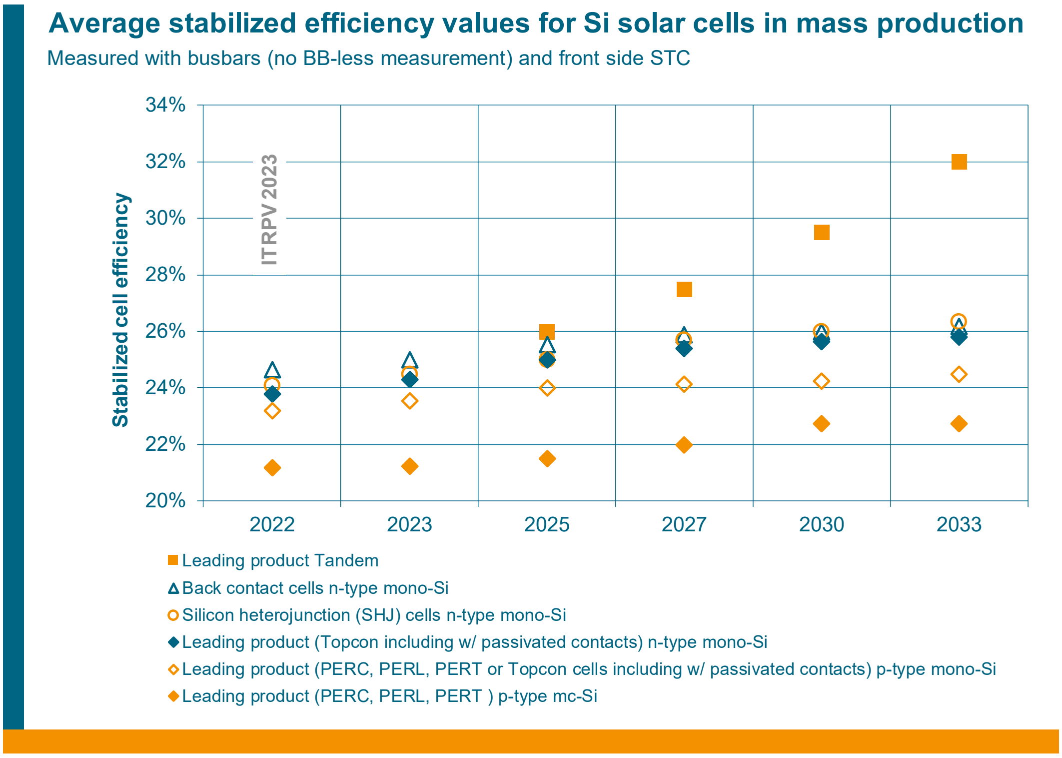


Fig. 38: Average stabilized efficiency values of c-Si solar cells in mass production.

Fig 38 illustrates the expected average stabilized front-side cell efficiencies of state-of-the-art mass production lines for double-sided contact and rear-contact cells on different wafer materials. The plot shows that there is potential for all technologies to improve their performance.

Cells using n-type material show the highest efficiency potential of today's cell technology concepts. We found that p- and n-type mono-Si cells with diffused pn junction at the front side will attain efficiency values reaching up to 24.5% and 25.8% respectively in the next 10 years. Cells on n-type using tunnel oxide passivated contacts at the rear side show higher efficiencies than all p-type cell concepts. Other n-type-based cell concepts like SHJ and back-contact cells, will reach higher efficiencies of up to 26.4% in mass production until 2033. We nevertheless see that the Si-based single junction cell concepts are converging to a practical efficiency limit of about 27%, close to the theoretical upper limit of around 30% [29]. Tandem cells will overcome this limit. Mass production cell efficiencies of Si based tandem cells concepts are expected to start at about 26%. The introduction in the market is expected after 2025 according to Fig. 38.

Fig. 39 shows that new built cell production facilities will make use of the economy of scale by increasing their annual production capacity. Factories with > 2 GW are dominating the manufacturing landscape today and fabs with > 5 GW annual cell production capacity will dominate the production landscape for new cell production capacities and on the long run.

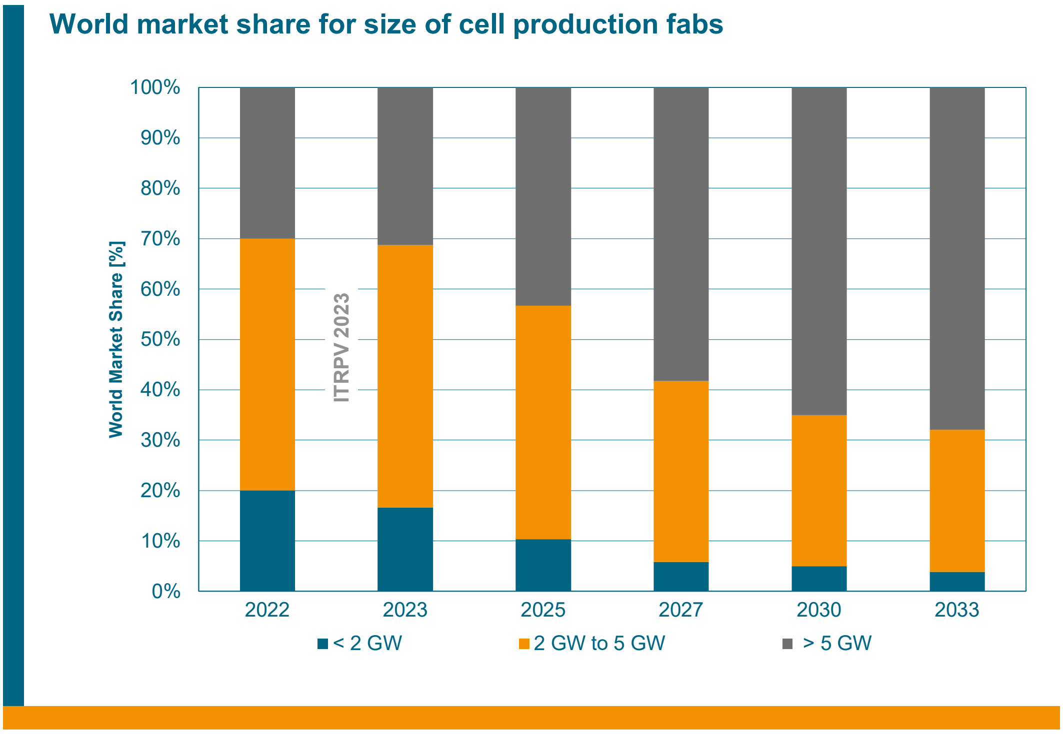


Fig. 39: Trend for name plate capacity of cell manufacturing fabs.

7. Results of 2022 | Module

7.1. Materials

Fig. 2 showed the price shares for mono-Si module products. The module related price share contributes with ≈ 40% to the module sales price. Cells are still the most expensive individual part of the module's bill of materials (BOM). The introduction of new, larger cell formats enables higher module powers and advantages in module efficiency at the expense of increased module size. Module conversion costs are dominated by material costs. Improvements of the module performance and of material costs are therefore mandatory to optimize module costs. Approaches for increasing performance like the reduction of optical losses (e.g., further reduced reflection of front cover glass), reduction of resistive losses, and the reduction of interconnection losses will be discussed in chapter 7.2. Approaches for reducing material costs include:

- Reducing material volume, e.g., material thickness.
- Replacing (substituting) expensive materials.
- Reducing waste of material.

All non-cell module materials contribute to module manufacturing cost with a similar portion. Glass is the most massive material of a module. It determines weight and light transmission properties. The thickness is also important for the mechanical stability of the module. Glass is used in standard modules as front side cover, in glass-glass modules (especially for bifacial applications) it is used as front as well as back side cover. Fig. 40 summarizes the trend of front side glass thickness.

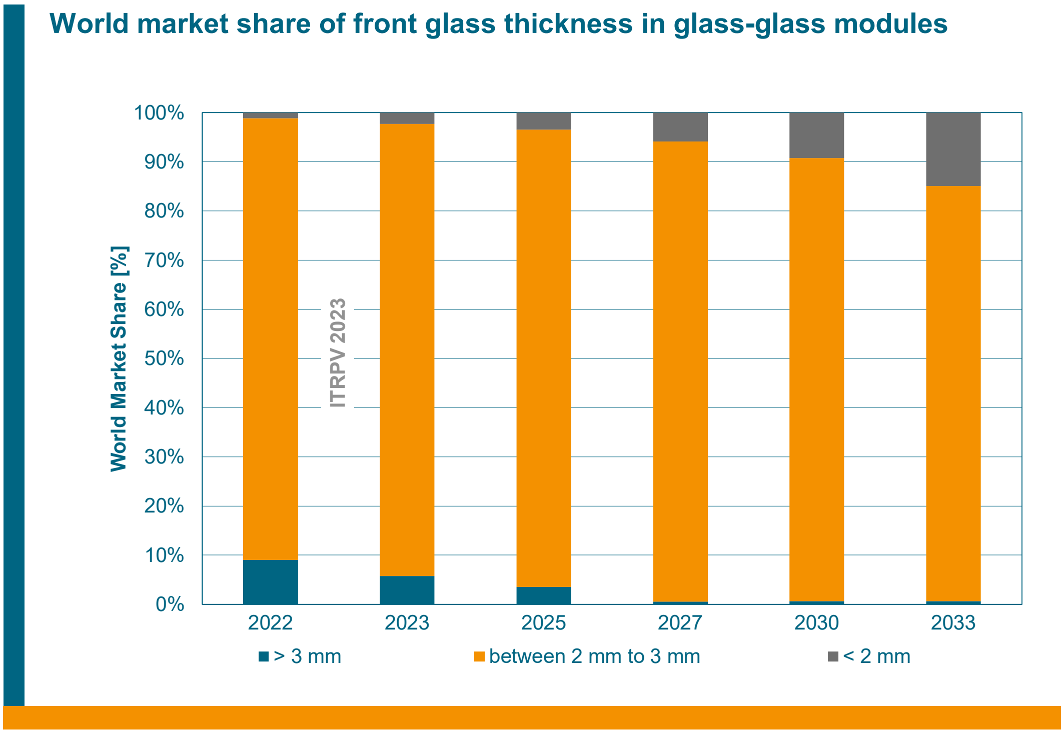


Fig. 40: Expected trend of front glass thickness in c-Si modules.

A thickness between 2 and 3 mm is mainstream today. It is expected that a reduction towards 2 mm thickness will proceed over the next years. A thickness below 2 mm is seen in the market with a share close to 2% in 2023, and expected increasing share over the next years. Thermal hardening is the dominant hardening method for front side glass.

Rolled/structured glass is mainly used in today's module manufacturing. The float glass market share of about 5% in 2023 will grow to about 10% within the next 10 years as shown in Fig. 41.

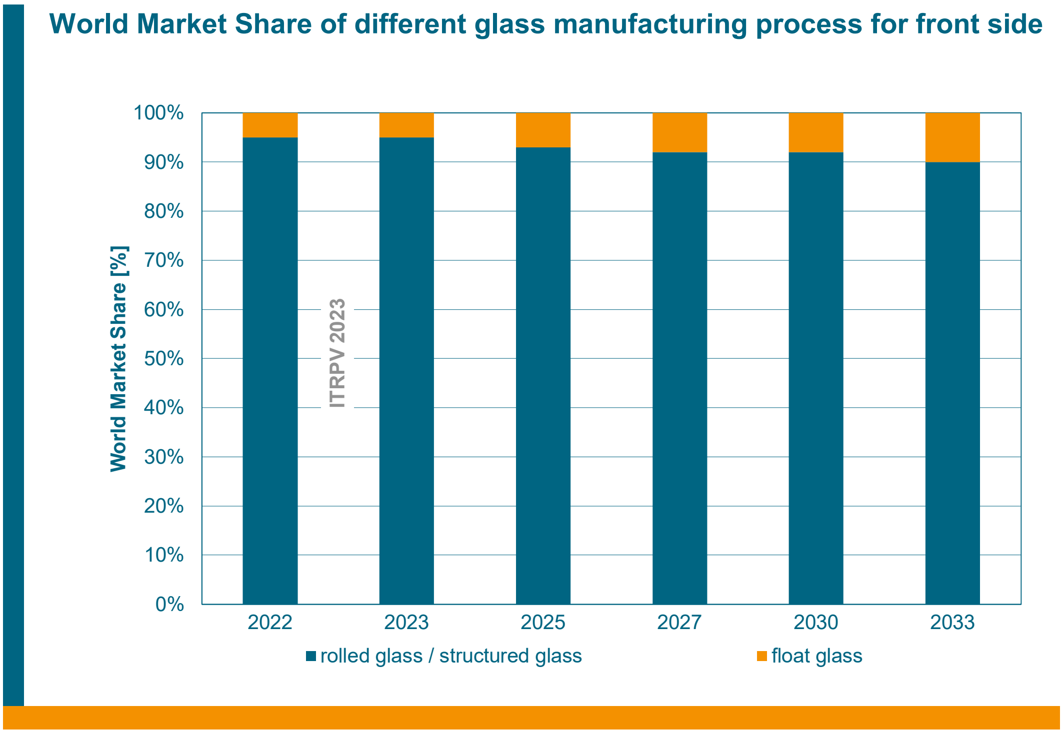


Fig. 41: Trend of front glass material market share.

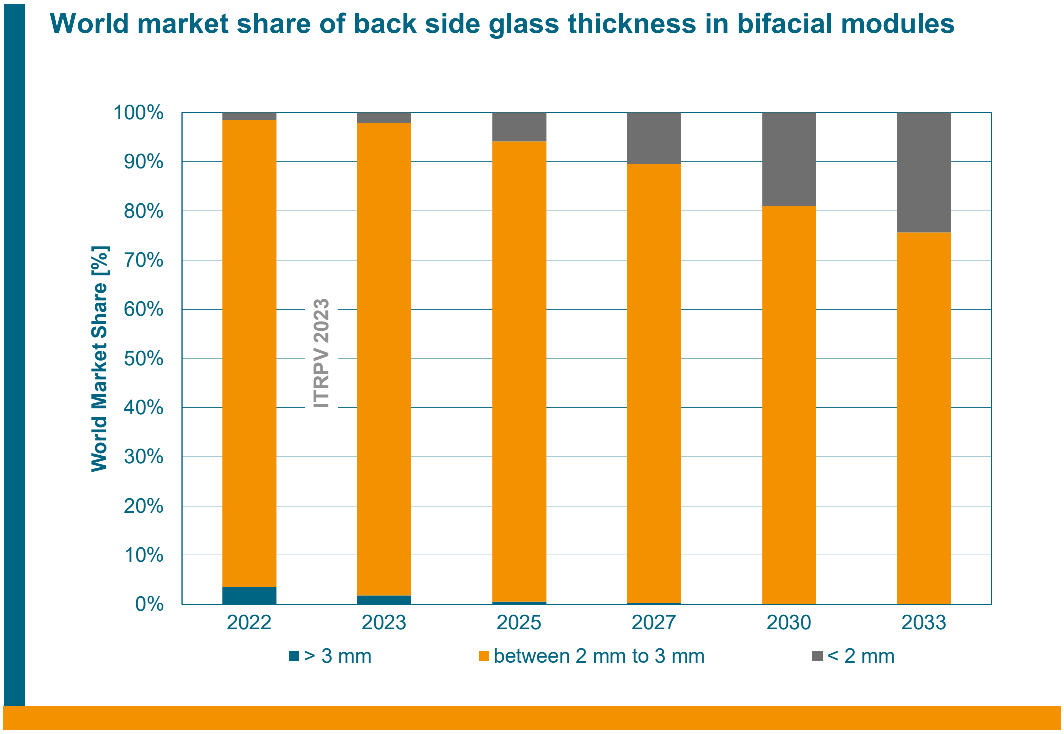


Fig. 42: Expected trend of back side glass thickness in bifacial modules.

Back side glass thickness is thinner than front side glass. Mainstream thickness is between 2 mm and 3 mm. Thickness below 2 mm has been in the market since 2022 and the market share is expected to increase in the upcoming years to above 20% in 2033; as shown in Fig. 42.

Rolled/structured glass is dominating the back side glass market today, but it is expected that more float glass will be used in the future with a share of about 50% in 2033; as shown Fig. 43.

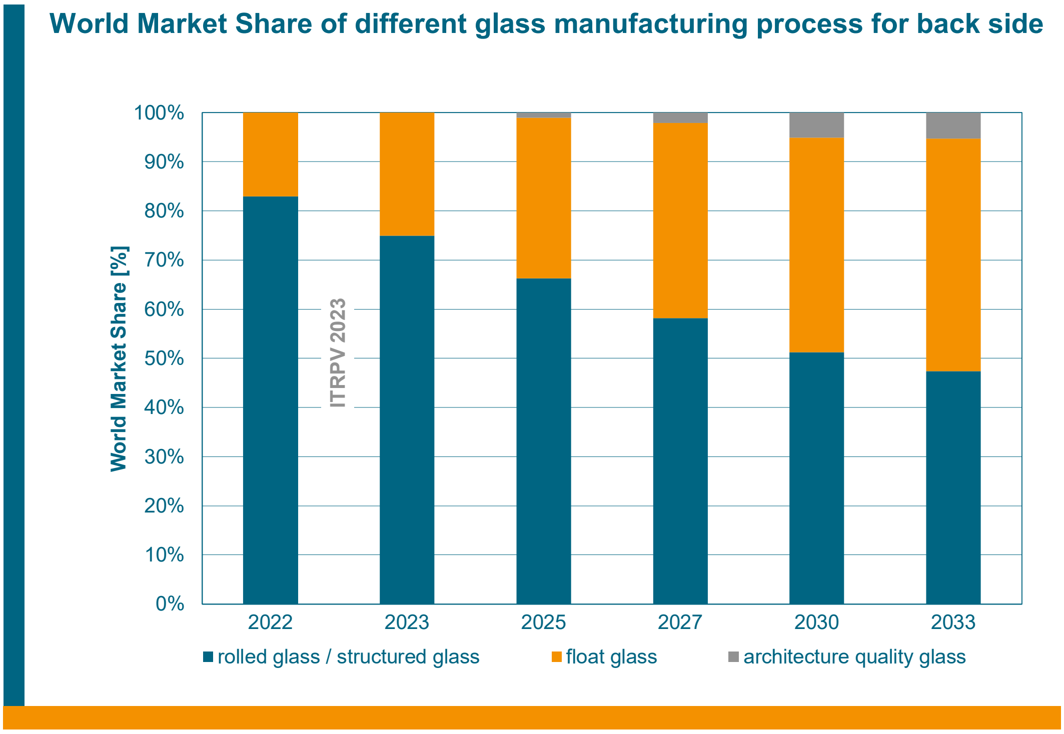


Fig. 43: Trend of back side glass market share.

The use of antireflective (AR) coatings has become standard to improve the transmission of the front cover glass. AR-coated glass will remain the dominant front cover material for c-Si PV modules in the future.

The transmission of AR coated glasses appears to be today around 94.2%, about 3% higher than for non-coated glasses. A continuous improvement of the glass is expected to reach up to 95% transmission within the next 10 years. Since AR-coated glass will be the most used front cover, it is important that the AR coating remains effective and stable under various outdoor conditions during the entire operational life of the module. All AR coatings on the market today meet an average lifetime of at least 15 years, and there is a clear trend indicating that the average service life of these coatings will improve to 25 years within the next 10 years.

Today, lead containing solders are used as the mature standard technology for reliable and cost-efficient interconnection of double-sided contact Si solar cells and interconnection of strings in the module manufacturing process. Lead-free interconnection alternatives exist for special application and for SHJ cells and IBC cell concepts. Fig. 44 and Fig. 45 show the expected market trends of different technologies for cell interconnection and for string interconnection in the module respectively.

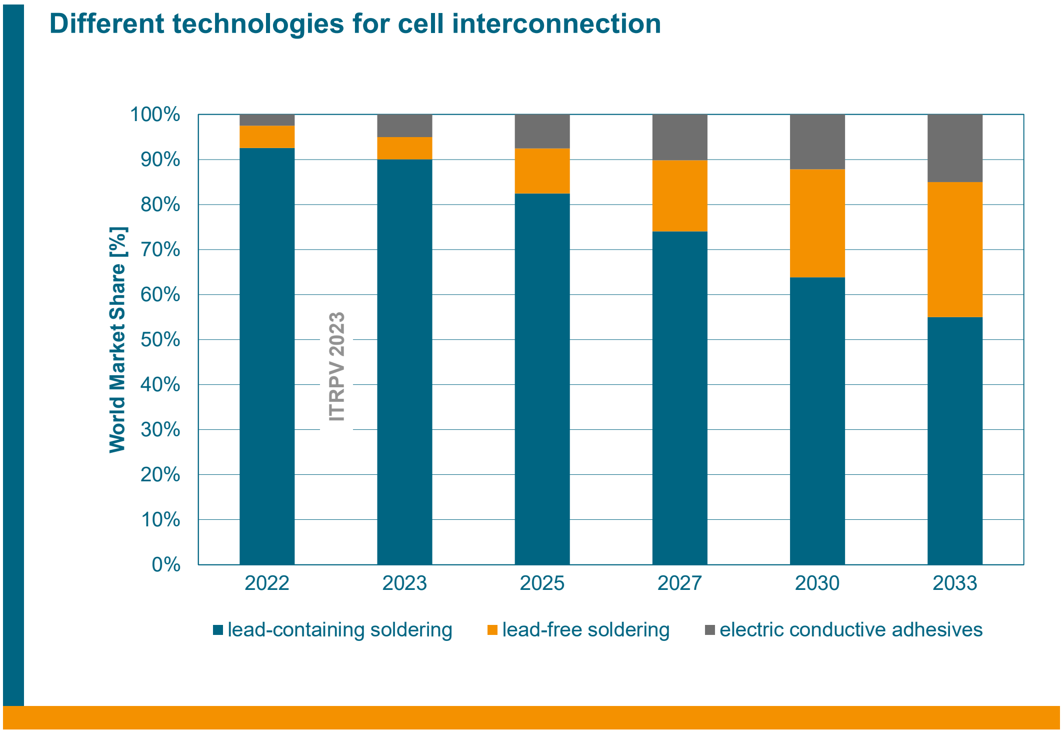


Fig. 44: Expected market share for different cell interconnection technologies.

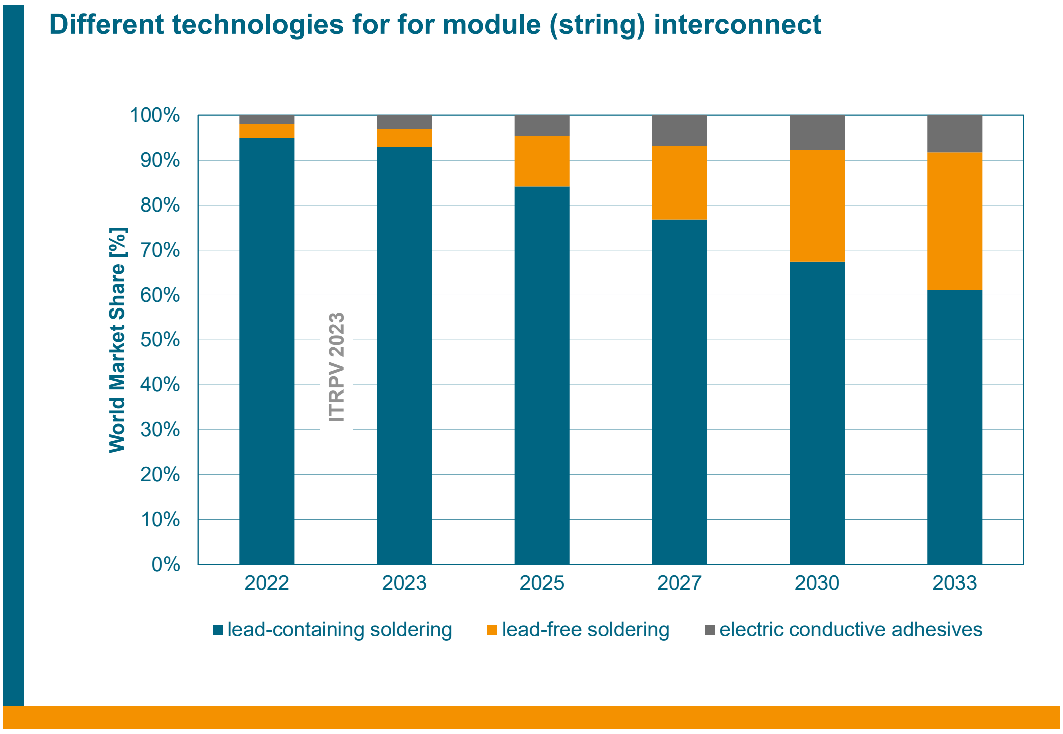


Fig. 45: Expected market share for different module interconnection technologies (i. e., for string interconnection).

Lead containing soldering is the expected mainstream technology for the next 10 years. Conductive adhesives for cell interconnection are expected to gain market share from about 2% in 2023 to about 15% within the next 10 years. Lead free soldering for cell interconnection, mainly driven by SHJ, is expected to gain market share from 5% in 2023 to 30% in 2033. The trends for string interconnection technologies in Fig. 45 show similar tendencies.

Materials containing lead are restricted in accordance with legislation that went into effect in 2011 under the EU Directive on the Restriction of Use of Hazardous Substances (RoHS 2) [30]. This restriction affects the use of lead and other substances in electric and electronic equipment (EEE) on the EU market. It also applies to components used in equipment that falls within the scope of the Directive. PV modules are excluded from RoHS 2, meaning that they may contain lead and do not have to comply with the maximum weight concentration thresholds of 0.1% as set out in the directive.[1] PV's exclusion and the thresholds will remain in effect at least until the ongoing review process of this directive is finished.[2]

Cell and module manufacturers should act carefully, especially, as the exclusion to the defined threshold in question is limited to PV panels installed in a defined location for permanent use (i.e., power plants, rooftops, building integration etc.). Should the component in question (the module) also be useable in other equipment that is not excluded from RoHS 2 (e.g., mobile charging applications), then the component must comply with the Directive's provisions at this stage.

Fig. 46 shows that copper wires, introduced some years ago for half-cell technology will stay the dominating cell interconnection material within the next 10 years. Copper ribbons will further lose market

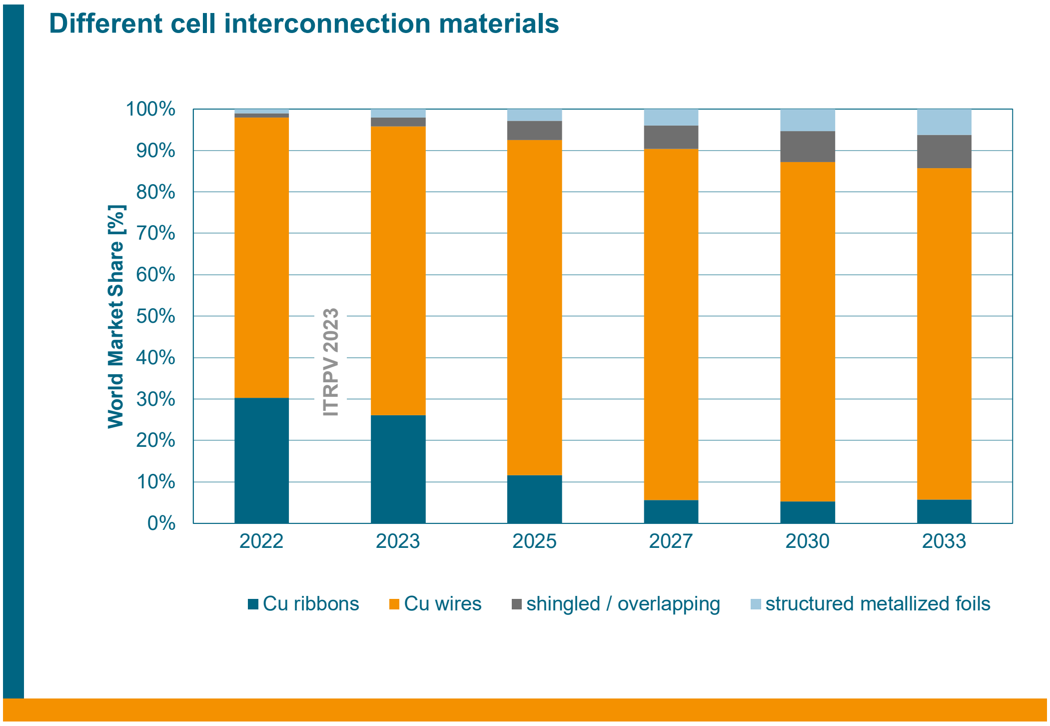


Fig. 46: Expected market shares for different cell interconnection materials.

[1] Article 2(i) of the RoHS Directive [2011/65/EU] excludes from the scope of the Directive "photovoltaic panels intended to be used in a system that is designed, assembled and installed by professionals for permanent use at a defined location to produce energy from solar light for public, commercial, industrial and residential applications."

[2] Article 24 of the RoHS Directive [2011/65/EU] requires an evaluation and possible revision of the Directive, including its scope, by July 2021. The consultation and process has not been finished so far and all exclusions are still valid.

share from 25% in 2023 to 5% after 2027. Within the next 10 years, overlapping interconnection technologies and structured foils will gain market share to about 6% and 8% respectively.

The expected trend of the thickness of copper wires for cell interconnection is shown in Fig. 47. Standard in 2023 are 295 µm. The diameter will reduce to 205 µm until 2033.

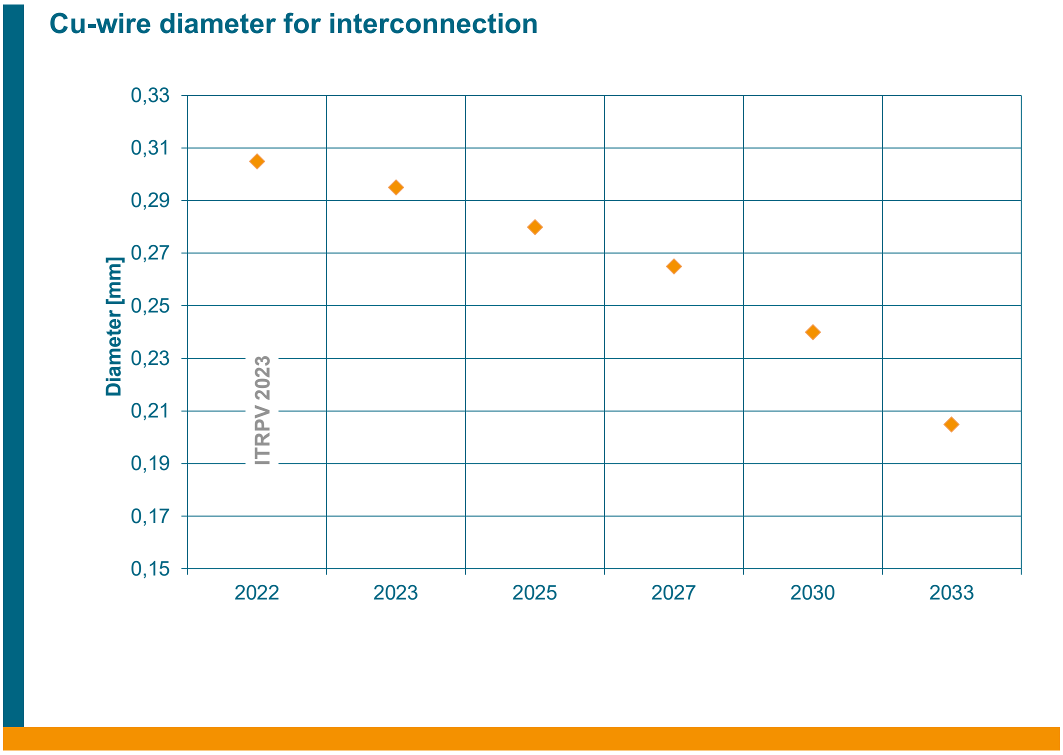


Fig. 47: Expected copper wire diameter for cell interconnection.

It is important to note that the existing and upcoming interconnection technologies will need to be compatible with all cell formats and upcoming cell technologies. In this respect, low-temperature approaches using conductive adhesives or wire-based connections have an inherent advantage due to the lower thermal stresses associated with them.

In Fig. 48 we see how module technology will be capable of processing thinner cells as discussed in chapter 5.3. Cell thickness reductions, according to Fig. 7, and Fig. 8, will not be limited by module technology. So, Si material savings have to and will contribute to future Wp cost reductions.

The encapsulation material and the back sheet / back cover materials are key module components to ensure long time stability. Both are also major cost contributors in module manufacturing. Intensive development efforts have been made to optimize these components regarding performance and cost. Improving the properties of this key components is mandatory to ensure the module service lifetime.

Fig 49 shows that EVA, mainstream in 2023 with about 70 % market share, will lose market share within the next years. White EVA is expected to keep a quite constant market share of about 10% over the next years. Polyolefins are an upcoming alternative especially for bifacial products in glass-glass combination and for SHJ [31]. We expect a significant increasing market share for Polyolefins of more than 50% within the next 10 years. Other materials are expected to keep low market share for niche applications.

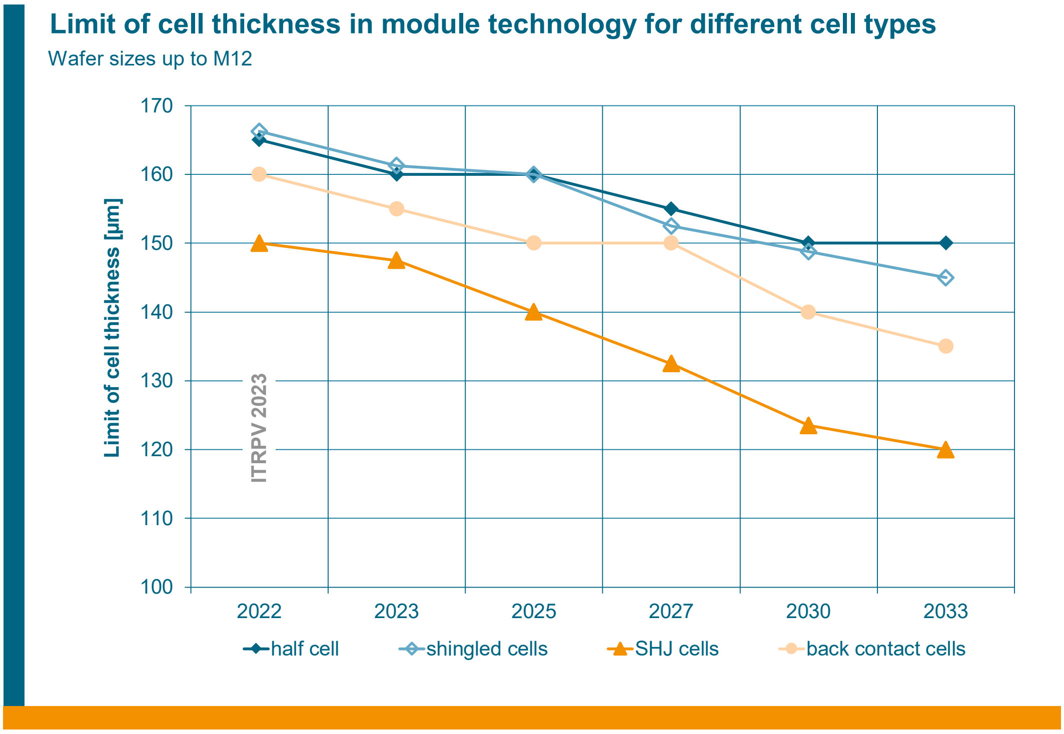


Fig. 48: Predicted trend of average cell thickness limit in different module technologies for wafer sizes ≤ G12.

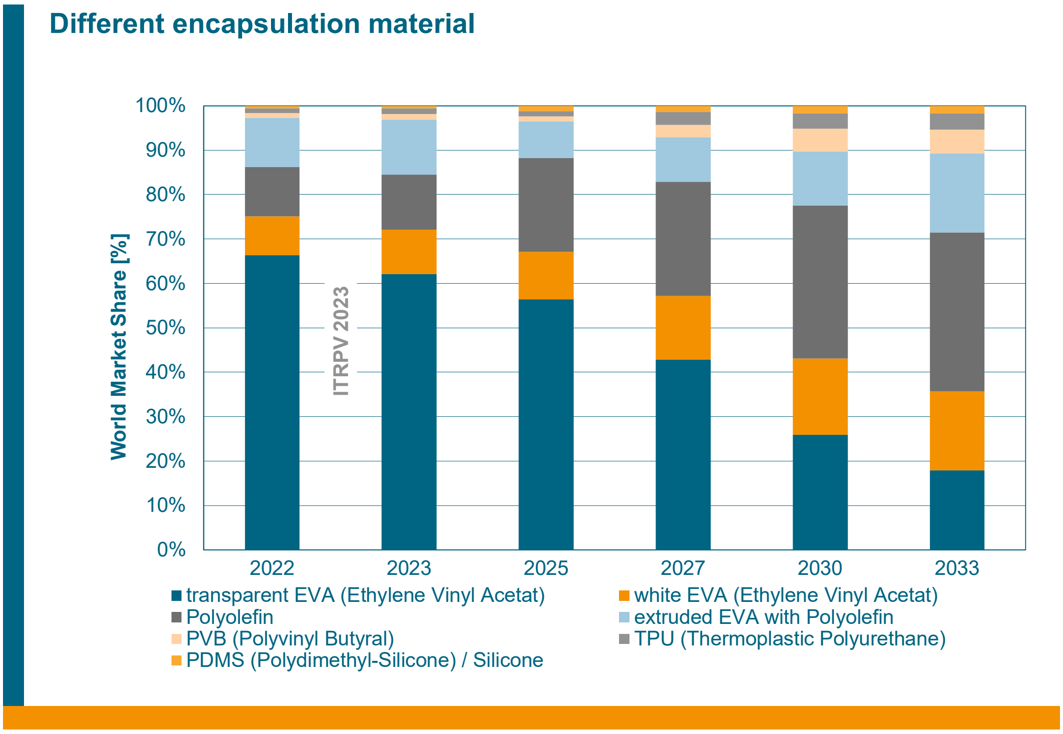


Fig. 49: Market share for different encapsulation materials.

Fig. 50 shows, that glass will become the dominant back cover material within the next years. Foils as back cover material will reduce their market share to about 40% within the next 10 years. Foil based front side covers will stay a niche. The thickness of the back glass will be reduced in the future to below 2 mm as shown in Fig. 42. Non-transparent backsheets will be used for monofacial modules. The share of white or black colored backsheets will stabilize at about 50% for each.

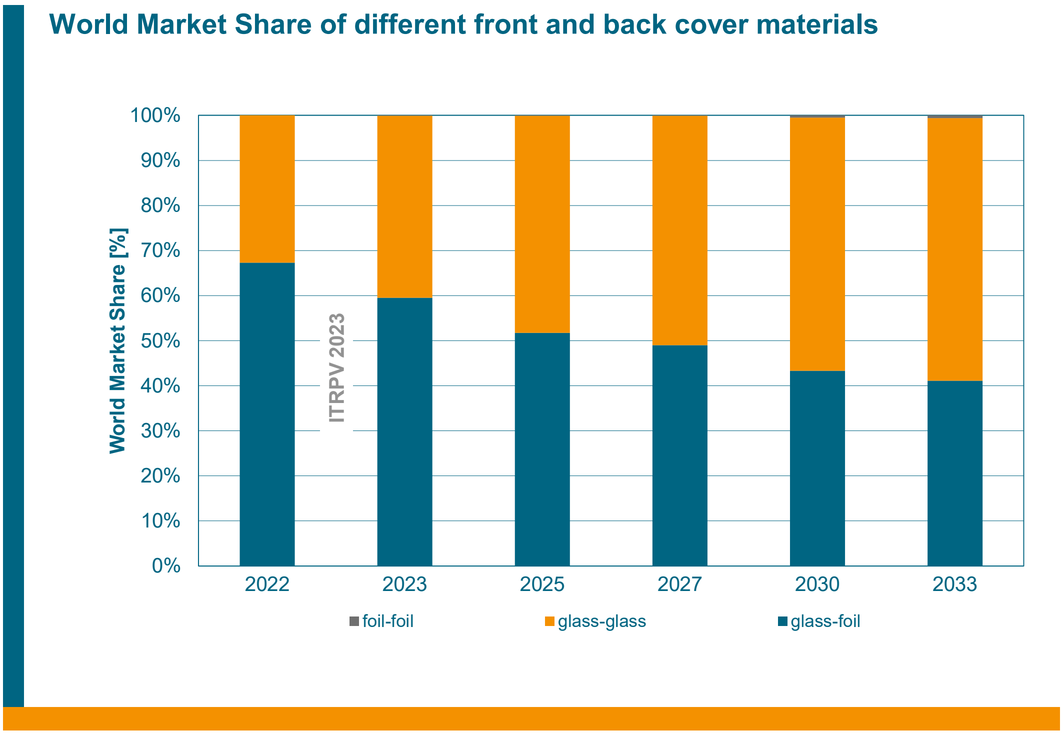


Fig. 50: Market share of glass and foil as front and back cover.

Fig. 51 looks at the trends for frame materials. Modules with aluminum frames are clearly dominating the market. Frameless modules are expected to increase in market share to about 10%. Steel as frame material is expected to increase its market share from 2 % in 2023 to about 11% until 2033. Plastics are considered as niche application with market shares of ≤ 2%.

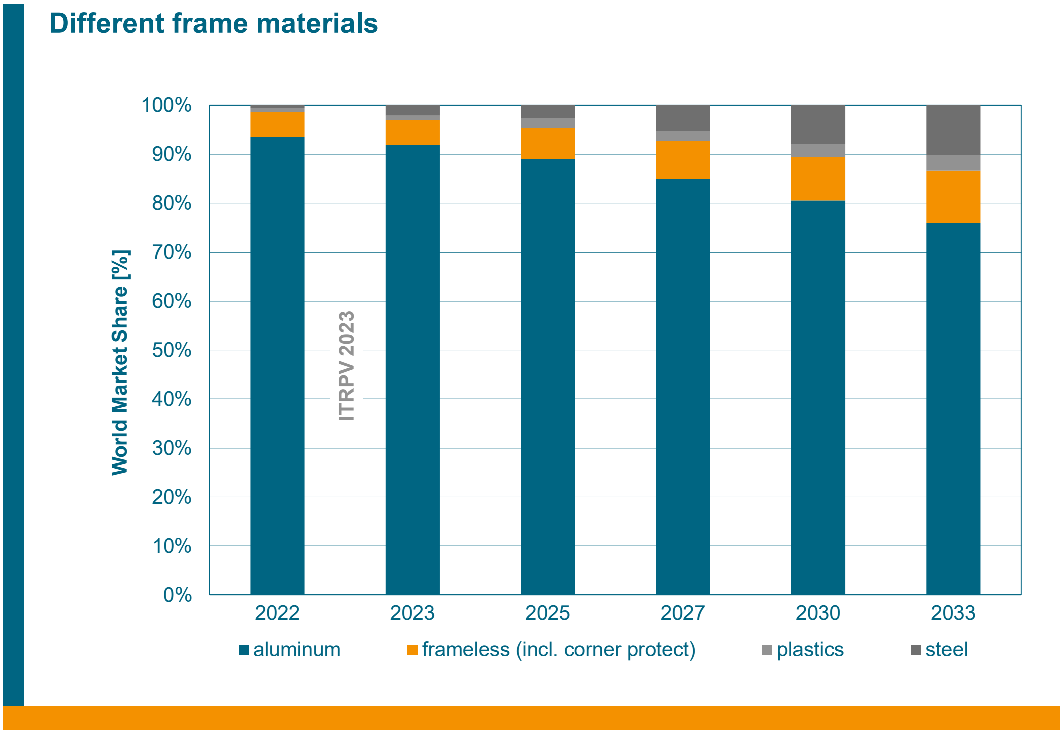


Fig. 51: Market shares for frame materials of c-Si modules.

7.2. Processes

A significant process innovation in module design during the last years was the introduction of half cells, in parallel with the introduction of wires instead of ribbons as described in Fig. 48. The deployment of half-cells is the dominating mainstream today for cells < M10 as shown in Fig. 52. Full cell technology market share will be reduced to below 2%. It will be used for IBC and in special module applications, third and quarter cells will stay for niche applications in this cell format also with a share of about 2% only.

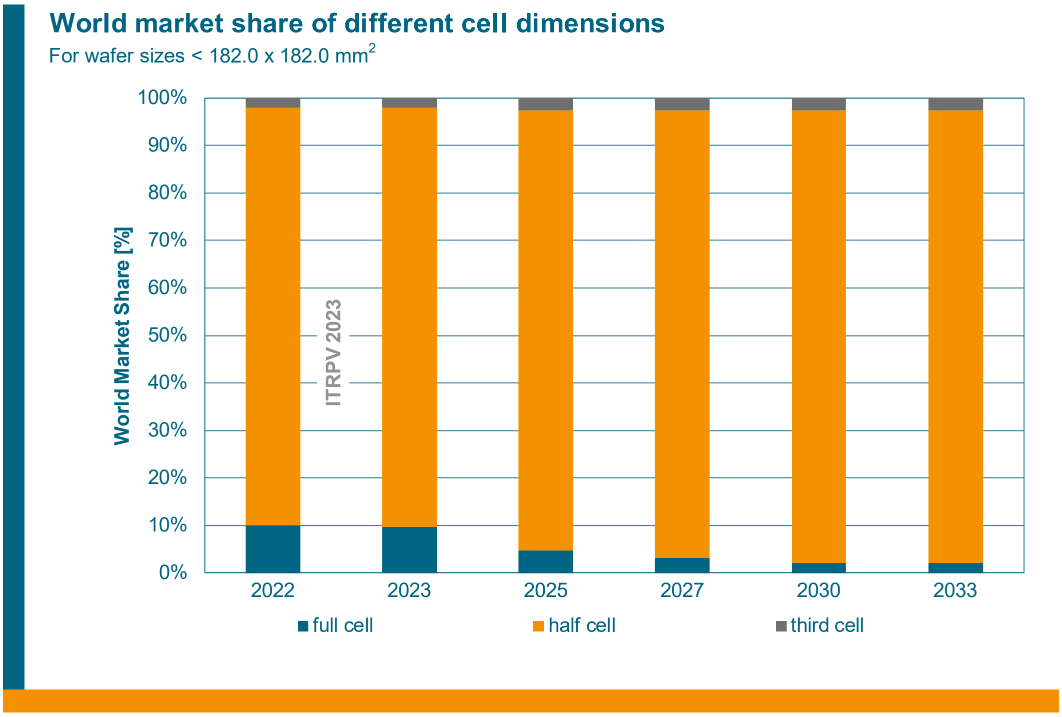


Fig. 52: Market shares of modules deploying full, half, third, and quarter cells ≤ M10.

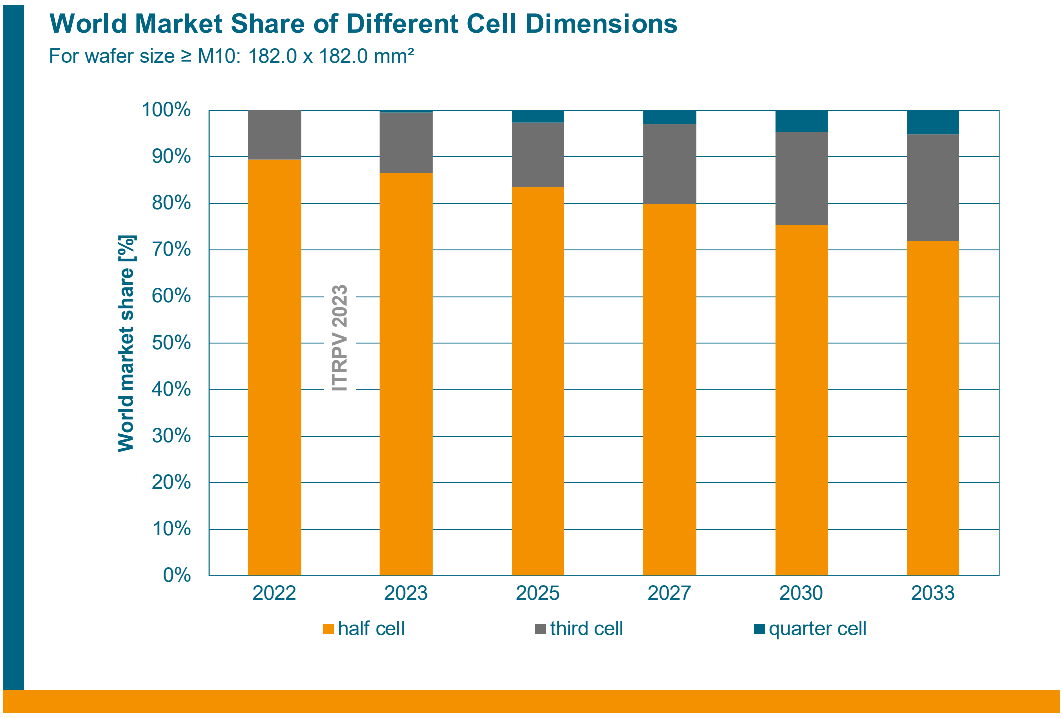


Fig. 53: Market shares of modules deploying half, third, and quarter cells ≥ M10.

Cells ≥ M10 are also using half cells mainly as the trend in Fig. 53 shows, full cells are not in use for large wafers. Third and quarter cells will be deployed, especially for G12. Fig. 54 shows that the trend for module production fabs is similar to the trend in cell production. Factories with annual capacities of > 5 GW will dominate the future production landscape. Nevertheless, smaller module fabs with < 5 GW, and < 1 GW are expected to be present for special applications and for regional markets.

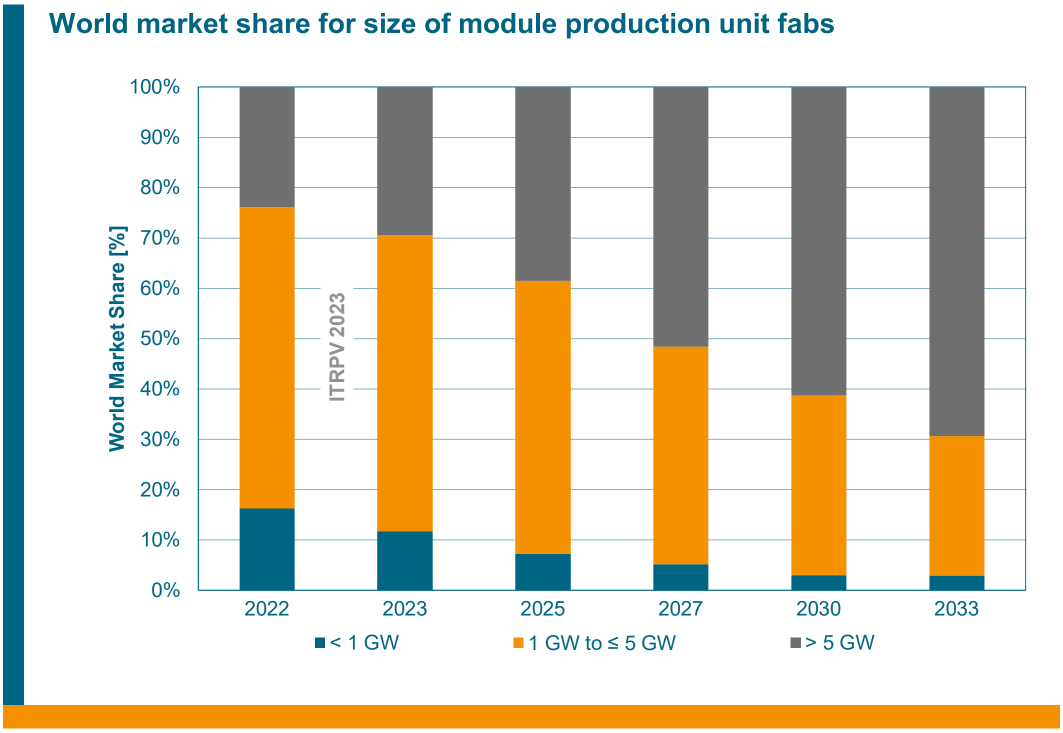


Fig. 54: Trend for name plate capacity of module manufacturing fabs.

7.3. Products

Due to the current diversification in wafer formats discussed in chapter 5.3., also module dimensions are changing. Comparing different module types only by the so far common module label power may be misleading as module powers with ≥ 600 Wp are possible with existing cell technologies [31, 32]. Therefore, the module efficiency is a useful parameter to compare different technologies and the final products. Module efficiency is calculated with module label power divided by the product of module area in m² and the irradiance at standard test conditions (1000 W/m²): (module label power / (module area x 1000 W/m²)). In today's module data sheets, the module efficiency is indicated - a value of 20% corresponds to a module area efficiency of 200 W/m². Fig. 55 shows the expected trend of average module efficiency for modules in mass production with different cell technologies.

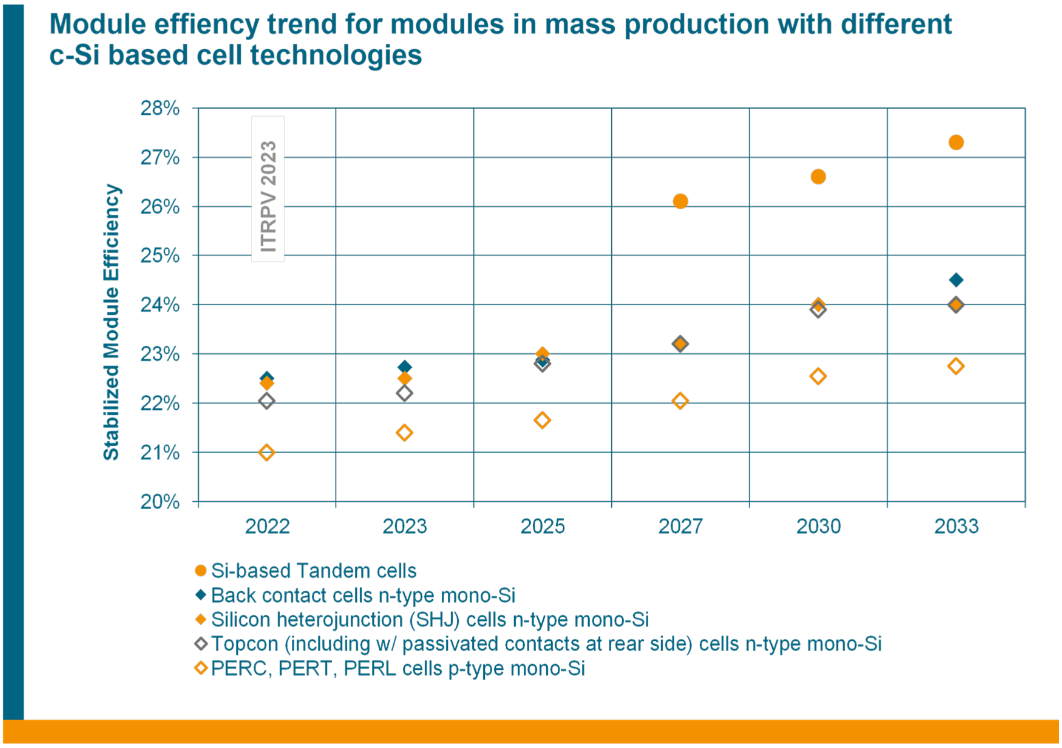


Fig. 55: Average module area efficiency in mass production for different c-Si solar cell technologies.

Current PERC p-type mono-Si modules are expected to show average efficiencies of 21.4% in 2023 and up to 22.5% within the next 10 years. Modules with n-type cells with tunnel oxide passivation technologies, are expected to be ahead of p-type PERC with 22.2% in 2023 and with up to 24% in 10 years. SHJ modules reach in 2023 an efficiency of 22.4% and are expected to attain 24% in 2033. Back-contact cells on n-type are expected to show again the highest module efficiencies, but in the same range with all n-type cell-based modules. We also report expected efficiencies for modules deploying Si-based tandem concepts. Si-based tandem modules are expected after 2025 with module efficiencies of 26% in 2027 and with close to 27.5% in 2033, respectively.

The big variety of new wafer sizes and wafer form factors in modules lead to various module dimensions. Only the width of modules based on M10 cells was fixed to 1134 mm. This is quite helpful especially in the rooftop market with its limited space requirements. Fig. 56 shows the trend of module size for residential applications – average module size will increase to beyond 1.8 m²: in 2023 modules < 1.8 m² account for about 15%. This share is expected to stay quite stable within the next 10 years.

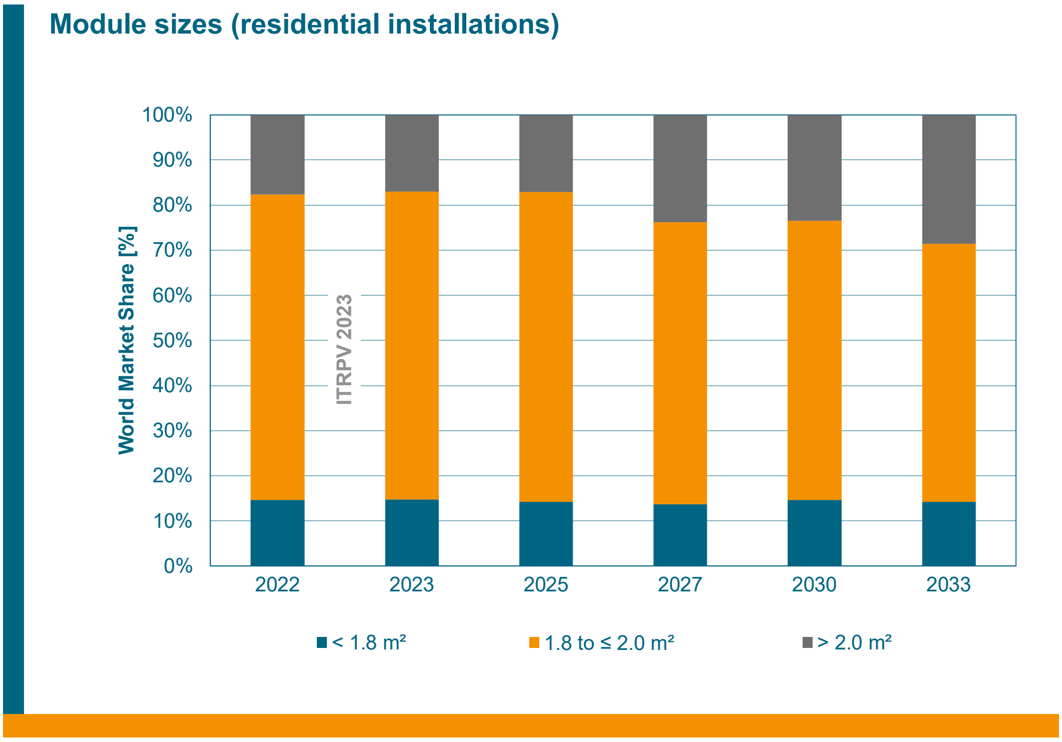


Fig. 56: Trend of module size for roof top applications.

Modules with a size between 1.8 m² and 2.0 m² will keep a share between 60% and 70%. Modules >2 m² are expected to have a market share between 18% and 28%.

The module size development for power plant installations is visualized in Fig. 57. The trend to larger modules is significant in this field. Module sizes up to 3 m² will be dominating the power plant market from– and larger modules >3 m² are expected to grow to about 10%.

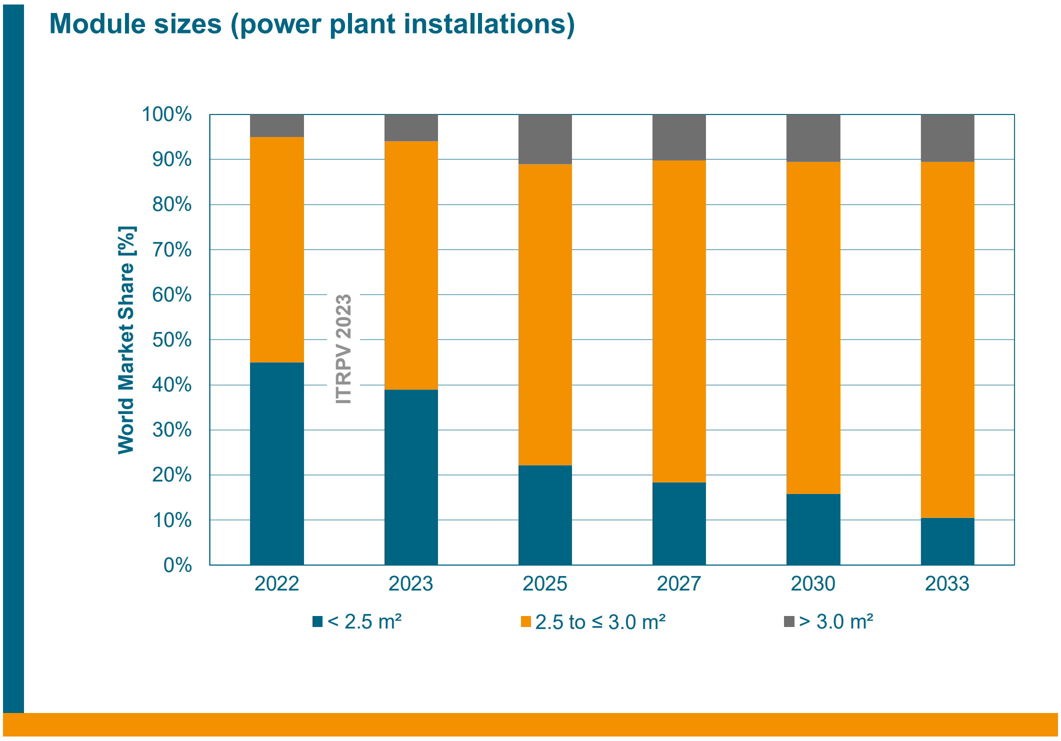


Fig.57: Trend of module size for power plant applications.

Larger modules will be heavier. Fig. 58 and Fig. 59 show the expected trend of module weight for residential and for power plant installations, respectively.

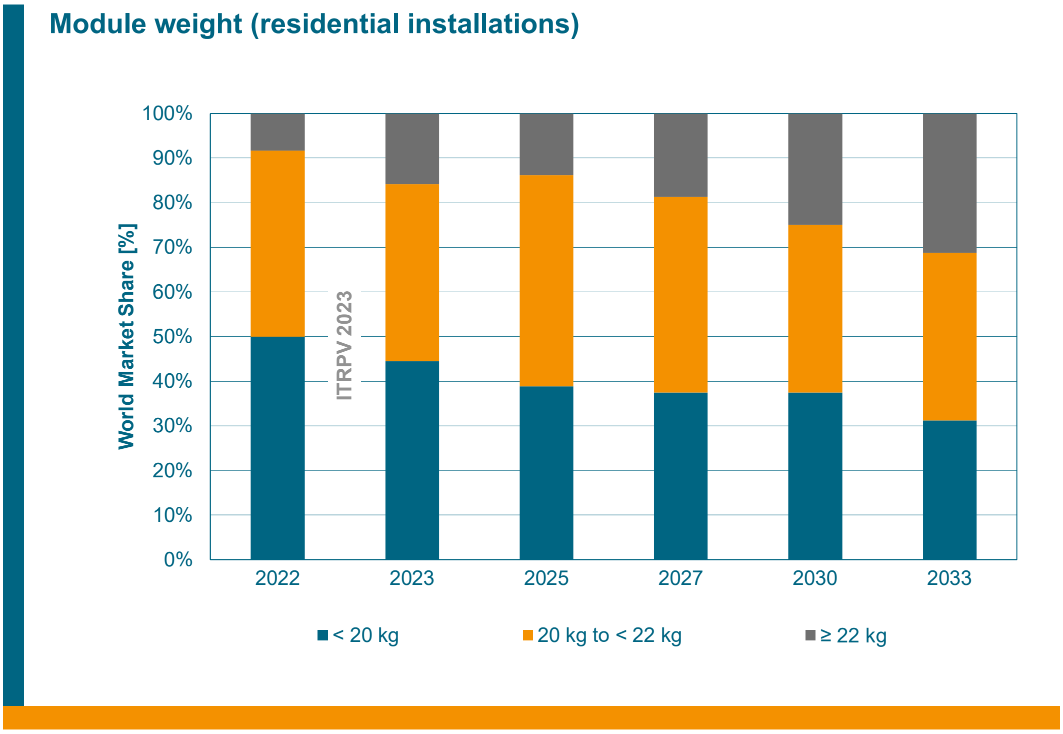


Fig. 58: Market share for the weight of modules for rooftop applications.

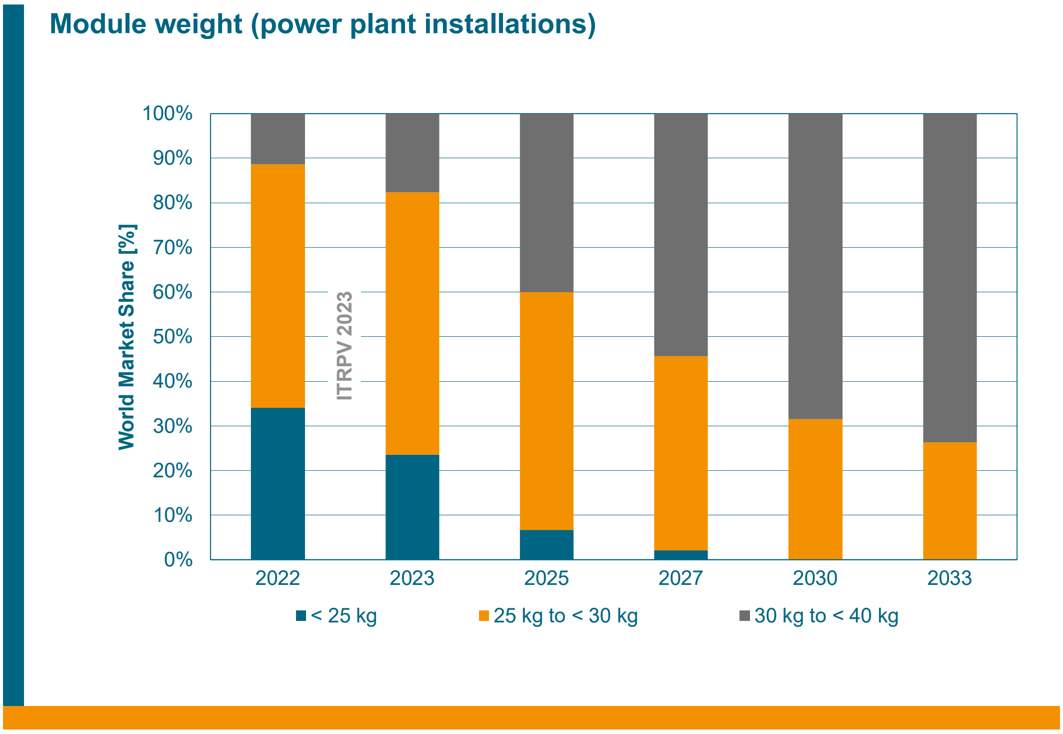


Fig. 59: Market share for the weight of modules for power plant applications.

Today, most of modules are monofacial modules – in 2023 about 65% as shown in Fig. 60. However, the share of bifacial modules will grow to about 70% within the next years. Bifacial cells can be used in bifacial modules as well as in conventional, monofacial modules. Bifacial cells are dominating the market as discussed in chapter 6.3 and as shown in Fig. 37.

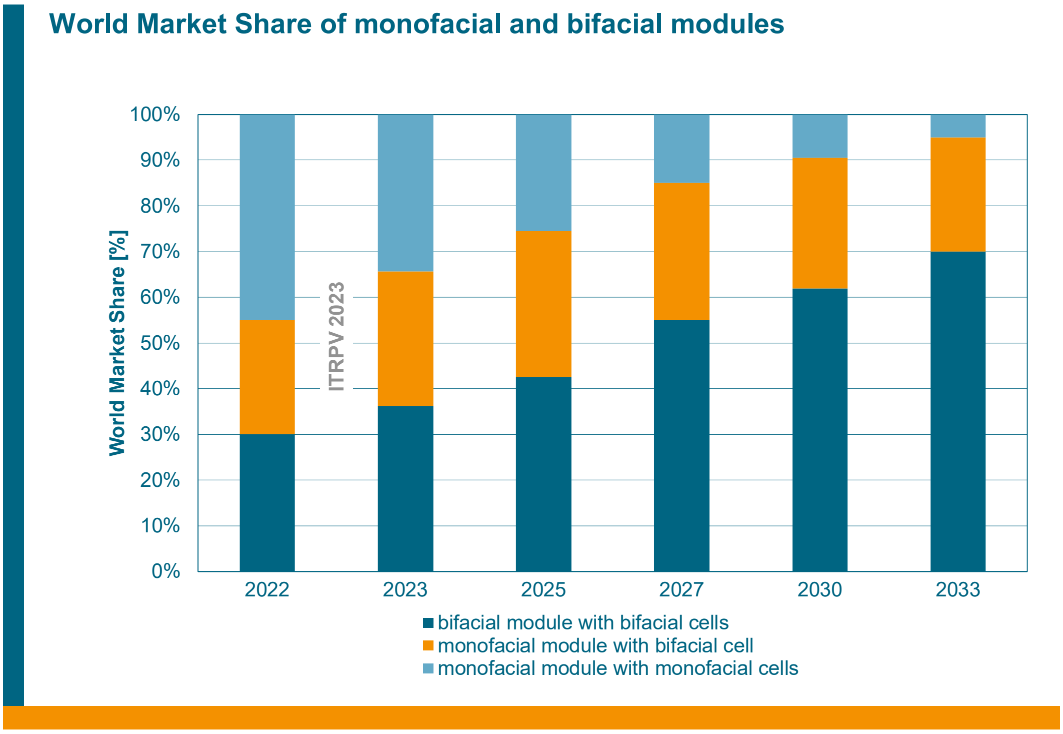


Fig. 60: Market share of bifacial modules.

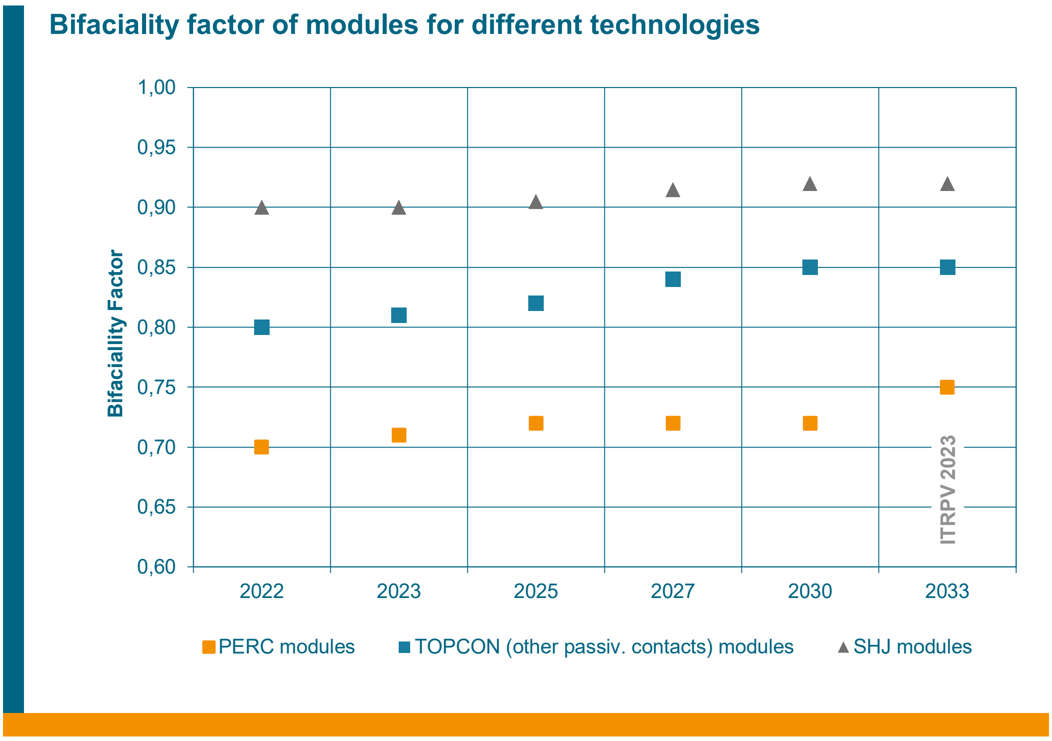


Fig. 61: Trend of bifaciality factor for modules with different cell technologies.

We expect that between 20% and 30% of bifacial cells will be used in monofacial modules. Bifacial modules will mainly be deployed in power plant installations.

An important parameter to characterize the performance of bifacial modules is the bifaciality factor. It describes the ratio between rear-side and front-side efficiency, measured under STC (standard test conditions). Fig. 61 shows the bifaciality factors of modules with different cell technologies. We see, that SHJ cells have the highest bifaciality factor that is expected to improve to up to 0.92. The bifaciality factor of standard PERC cells is expected to improve from about 0.71 in 2023 to 0.75 within the next 10 years. TOPCon cells show a bifaciality in between that of SHJ and PERC.

Another trend in module technology is the development of modules for special markets and environmental conditions. Fig. 62 shows the assumed market share of modules for special environmental conditions. It is still expected that the main market will be for standard modules. Modules for special environmental conditions like tropical climate, desert environment, or floating will together account for up to 20% over the next 10 years.

The junction box (J-box) is the electrical interface between the module and the system. So-called smart J-box technologies are deployed to improve the power output of PV systems. Smart J-boxes will increase their market share to about 20% within the next 10 years as shown in Fig. 63. So, the participants in our survey believe that standard J-box without any additional function except the bypass diodes will clearly dominate the market.

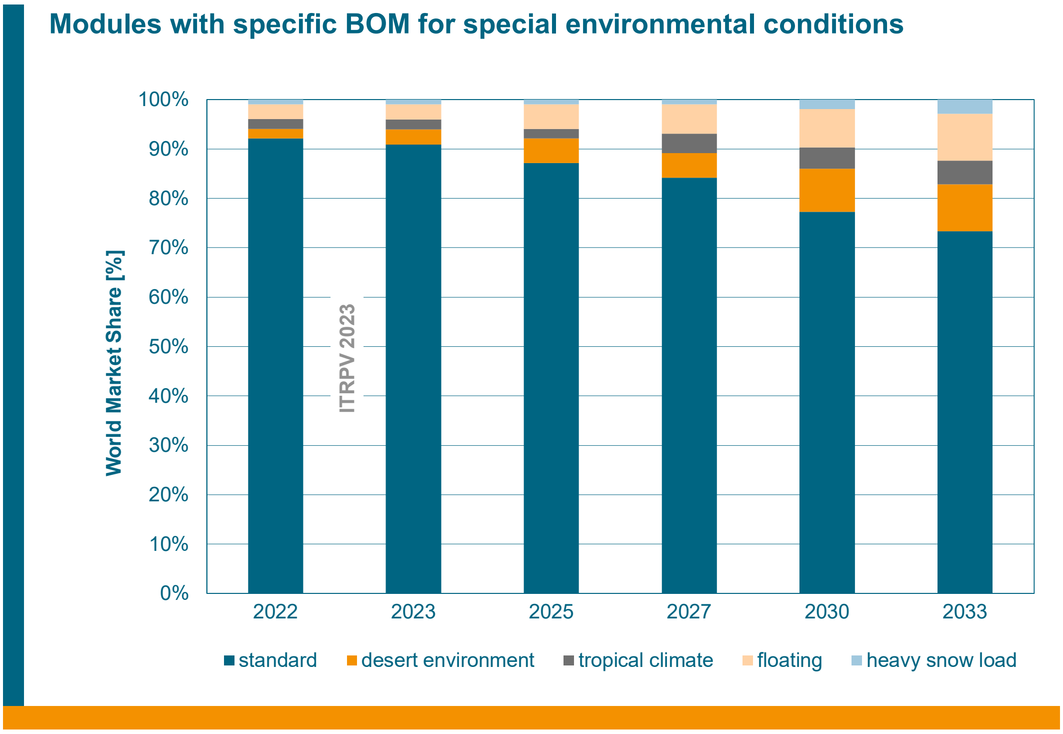


Fig. 62: Market share for special regional applications.

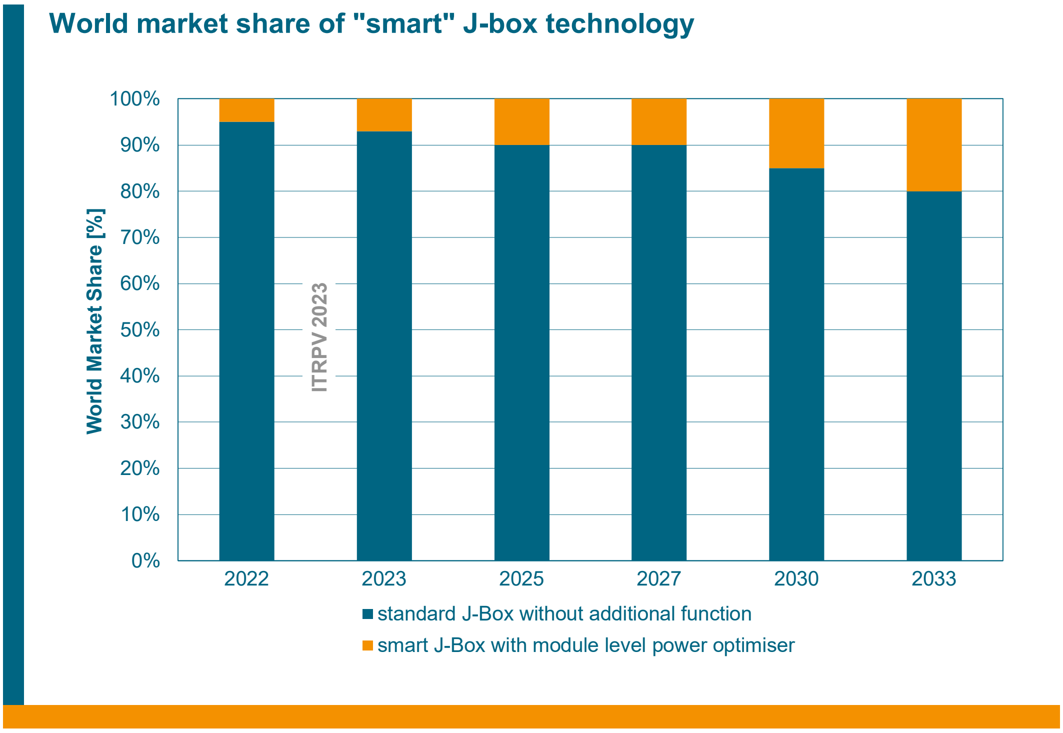


Fig. 63: Market share for different J-box functionality - smart vs. standard J-box.

The trend for J-box with special internal functions is shown in Fig. 64. Special features will be used in special markets. Standard junction boxes without additional functions will stay mainstream.

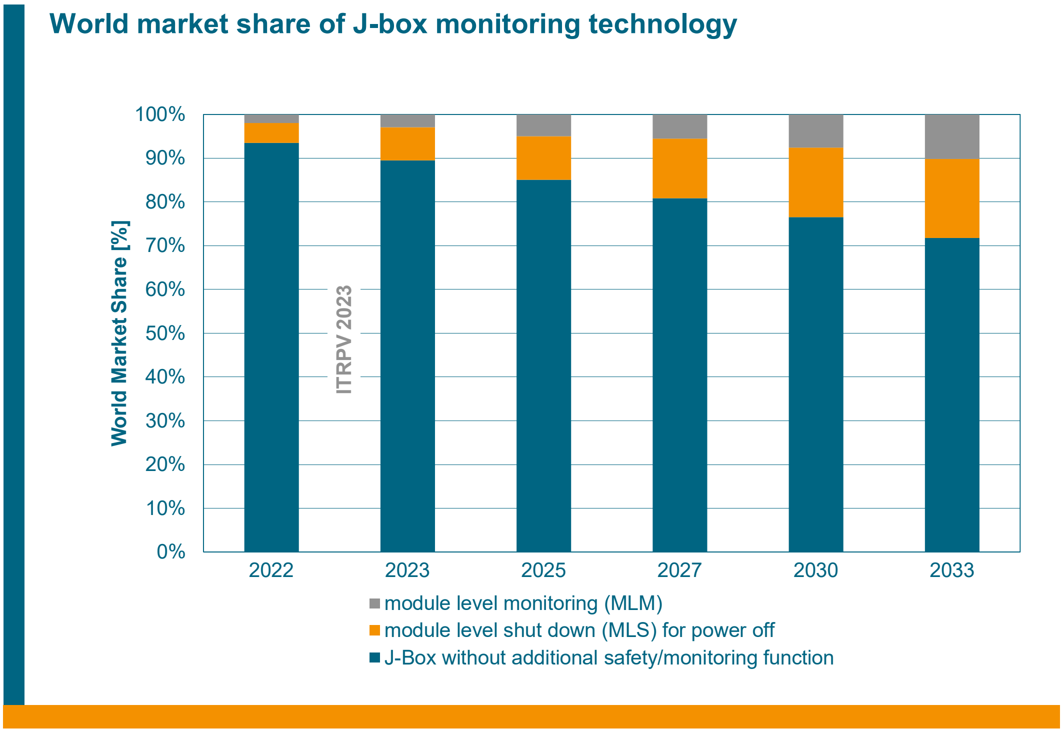


Fig. 64: Junction box monitoring technology.

Fig. 65 shows the trend of module product and module performance warranty for the next years (module and system degradation comparison behavior is shown in Fig. 71). The product warranty is expected to increase from 12 to 15 years. Performance warranty is expected to increase to 30 years from today's 25 years. The degradation after the 1st year of operation will be reduced from 2% to 1%. Annual degradation is expected to be reduced slightly from 0.55% in continuously to below 0.4% within the next 10 years; please refer to Fig. 71.

The control of light induced degradation (LID) and of the light and elevated temperature induced degradation (LeTID) enabled these warranties. Understanding the degradation mechanisms and a tight control of the degradation were the basis [19, 33]. The implementation of gallium doped wafers for p-type PERC as discussed in chapter 5.2.1 as well as the availability of a standard for LeTID testing [34] are supporting this trend.

In order to maintain quality (for thinner cells as well), the solar cells used for module assembly should be free of micro-cracks. The contributors consider Potential Induced Degradation (PID)-resistant cell and module concepts also as market standard.

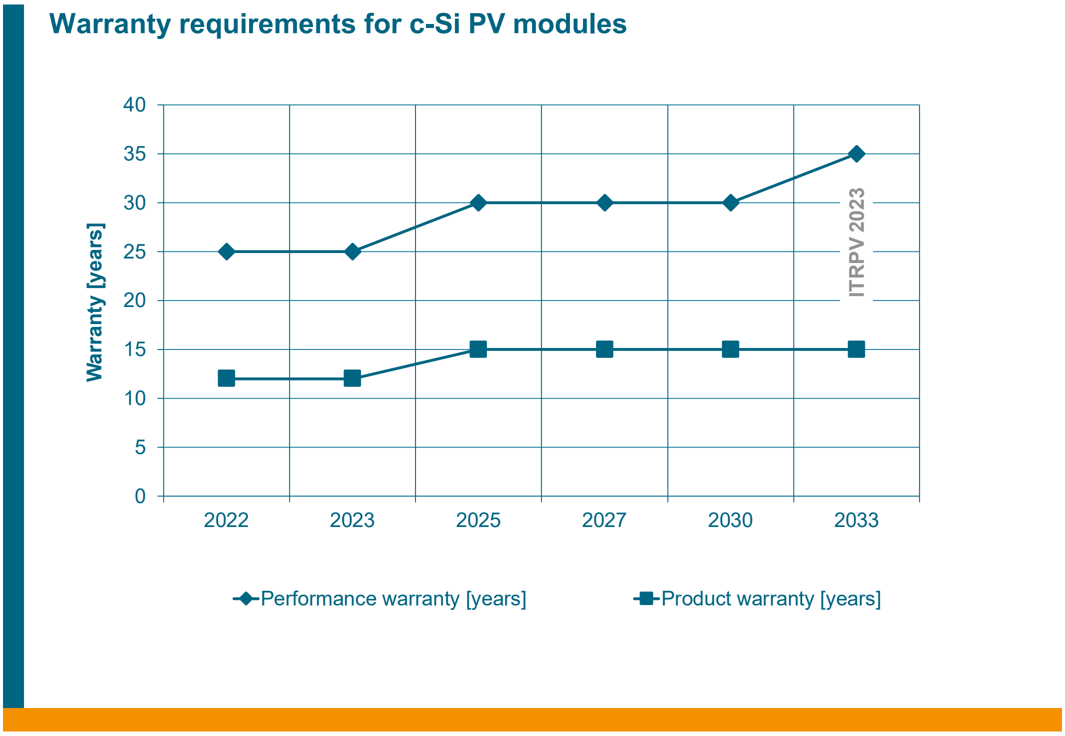


Fig. 65: Expected trend for product warranty and degradation of c-Si modules.

8. Smart Fab Status

Using the tools in an efficient way is mandatory to keep path with required cost reductions. Fig. 66 summarizes the status of Overall Equipment Efficiency (OEE) according to SEMI E10 [35] in state-of-the-art cell production facilities for M10 wafer size. All tool groups show now OEE values >90% with the trend to further improvement to 95%.

OEE Improvements will mainly be realized by improving tool and fab automation, automatic recipe downloads, via integration of the tools into Manufacturing Execution Systems (MES). This includes automatic dispatching systems, automated wafer-to-wafer and lot-to-lot process control systems. In addition, yield improvements must be assured despite the introduction of thinner wafer. The trend for inline process control in cell and module production lines is shown in Fig. 67.

Characterization methods are deployed to ensure high production yields, high average efficiencies with tight distributions, perfect optical appearance, and longtime product reliability. These methods include incoming wafer inspection, in-line monitoring, and Automated Optical Inspection (AOI) systems; especially during the metallization processes. The integration of those methods in production lines will increase more and more with time.

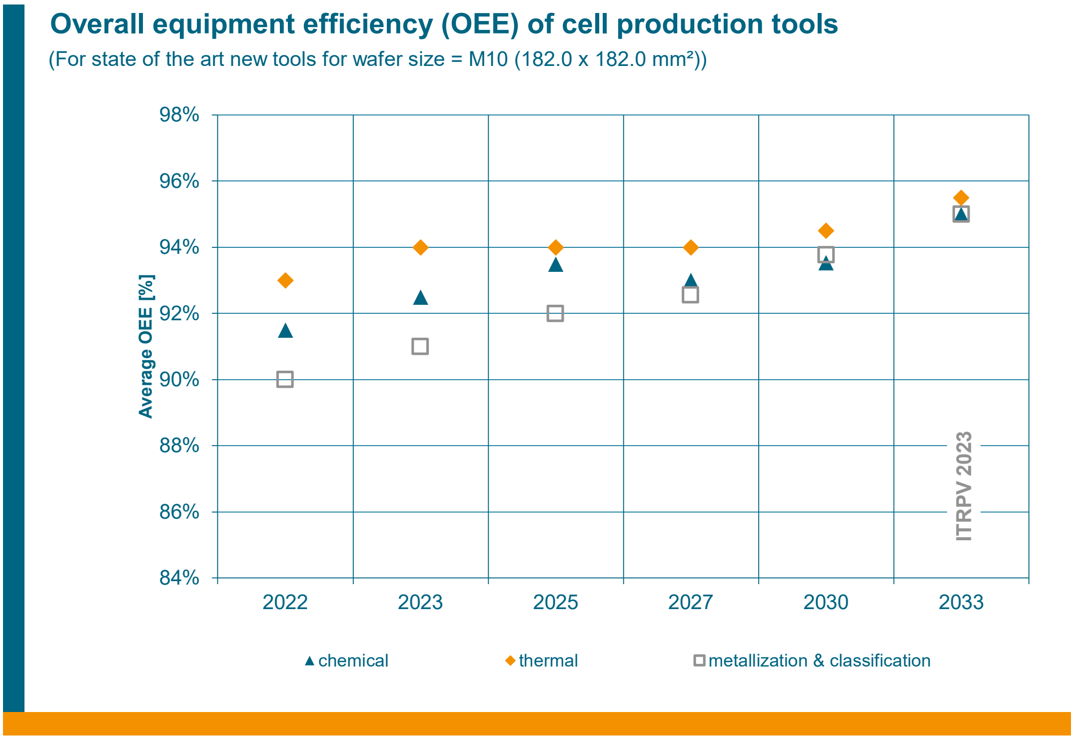


Fig. 66: OEE trend of state of the art new cell tools in new production facilities.

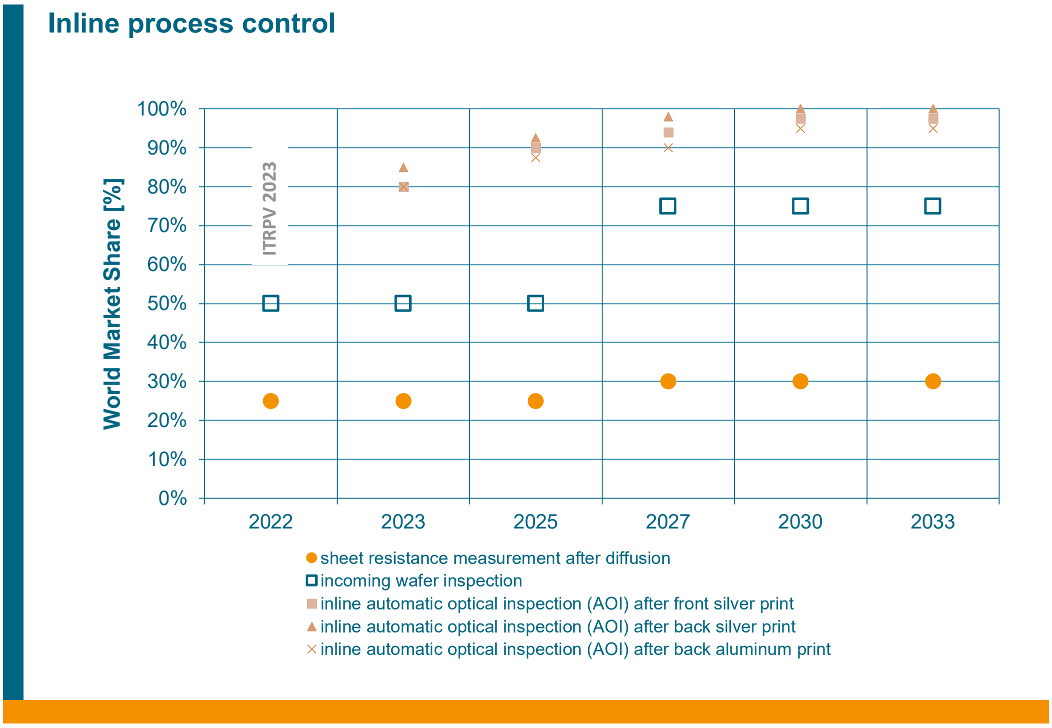


Fig. 67: Market share of inline process control for incoming wafer quality, sheet resistance, antireflective layer deposition, and for printing quality at rear and front side printing.

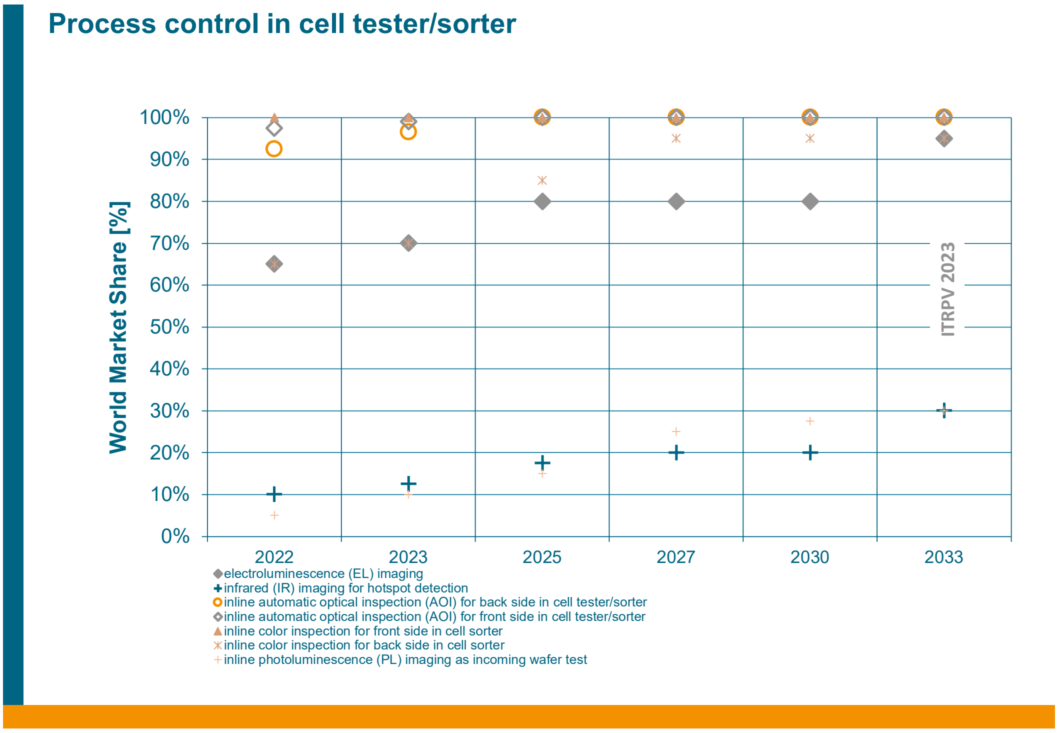


Fig. 68: Market share of different inline Automated Optical Inspection (AOI) systems for process control at cell test.

Fig. 68 shows that AOI of front and back side as well as front side color inspection are standard in cell test and sorting. In addition, we see an increasing share of rear side color inspection for bifacial cells and increasing deployment of EL, IR, and PL imaging systems. The further increase of implementation in the upcoming years is expected.

The trends for inline testing and manufacturing execution systems (MES) in module production lines are summarized in Fig. 69.

In-line EL inspection of modules and cell AOI in stringer are standard today. IR and cell color inspection in the stringer in module production are expected to stay on low levels as those inspections are already done at cell test. MES in module lines and AOI implementation as inspection after lamination are expected to increase within the next 10 years to 100%. This is a clear sign towards further automation and smart manufacturing in c-Si module production.

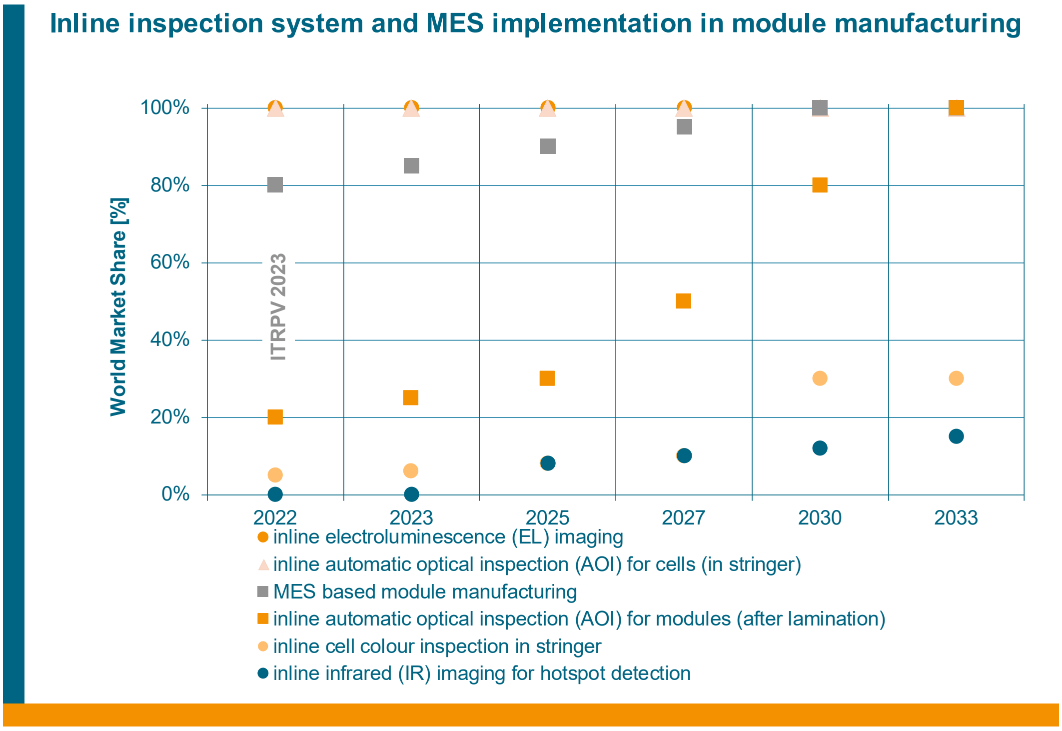


Fig. 69: Trends of inline inspection systems and MES implementation in module production lines.

9. Results of 2022 | System

9.1. Components

Module, balance of system (BOS) components, and project development costs are the largest contributors to PV LCoE. The global average costs for these items increased in 2022 due to supply chain constraints, material price increase, and other inflation-related pressures. Fig. 70 shows the expected trend for median global system costs and the relative contribution from each component for large systems > 10 MWdc. The trend considers systems from across three regions: Europe, Asia, and the US.

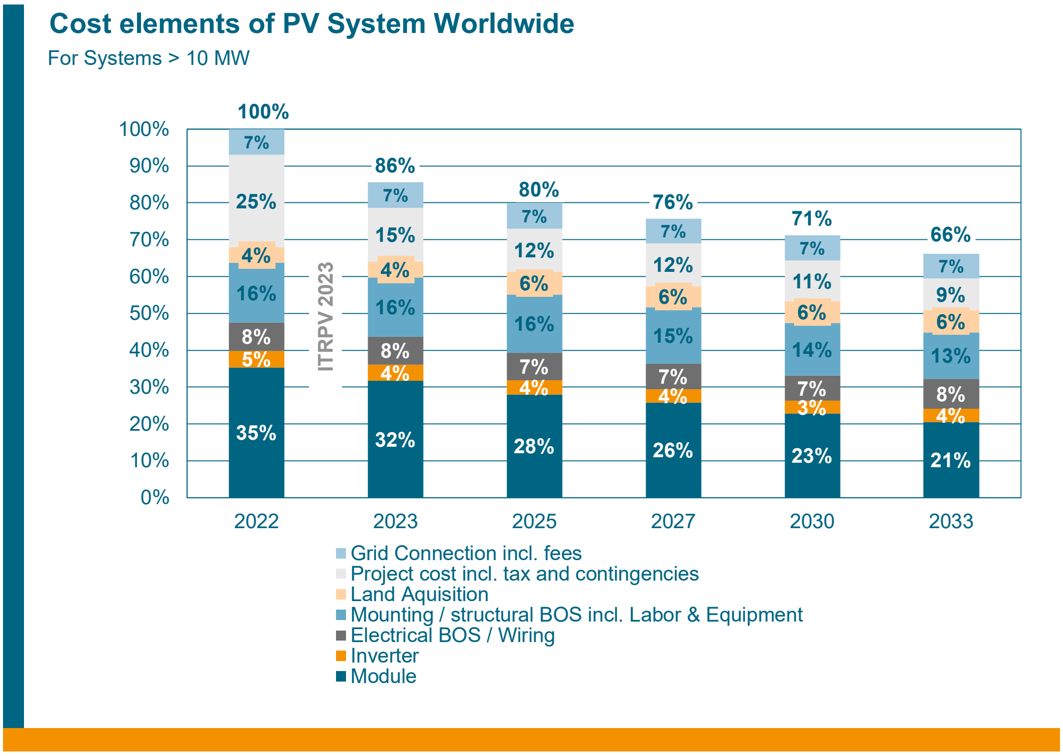


Fig. 70: Relative median global large scale system component costs in 2022 and projections to 2033.

The ITRPV results for this year again reflect that PV system capital costs vary significantly by continent. The results are 770 US$/kW-dc median capital cost for utility-scale systems in the EU, 705 US$/kW-dc median capital cost for utility-scale systems in Asia, and 1,410 US$/kW-dc median capital cost for utility-scale systems in the United States. The so-called 'soft costs' including project developer costs, overhead and profit, sales tax, and permitting fees typically have the greatest variance across the globe and across projects. 2022 utility-scale PV system soft costs and module costs in the United States were, respectively, around 0.50 US$/W-dc and 0.09 US$/W-dc higher than the median costs for the EU and Asia. The worldwide average utility-scale system cost trends reflect declines from 966 US$/kW-dc in 2022 to around 608 US$/kW-dc in 2033.

Around 35% total PV system cost reduction is expected within the next 10 years due to ongoing technology improvements and increasing scale. The global median price for modules is projected to drop from around 0.32 US$/W in 2022 to 0.18 US$/W in 2032; but the median global price for inverters, electrical BOS and structural BOS is not projected to change significantly by 2033. The majority of non-module cost reductions are projected to come from lower project developer costs, and lower profit and overhead. An important parameter is the degradation rate of the whole PV system. Fig. 71 shows the expected average annual degradation rates of PV systems in comparison with the module degradation trend shown in Fig. 65. Annual system degradation is expected to improve over the next 10 years.

Fig. 72 shows the expected trend for the technical lifetimes for the main electrical components of PV system.

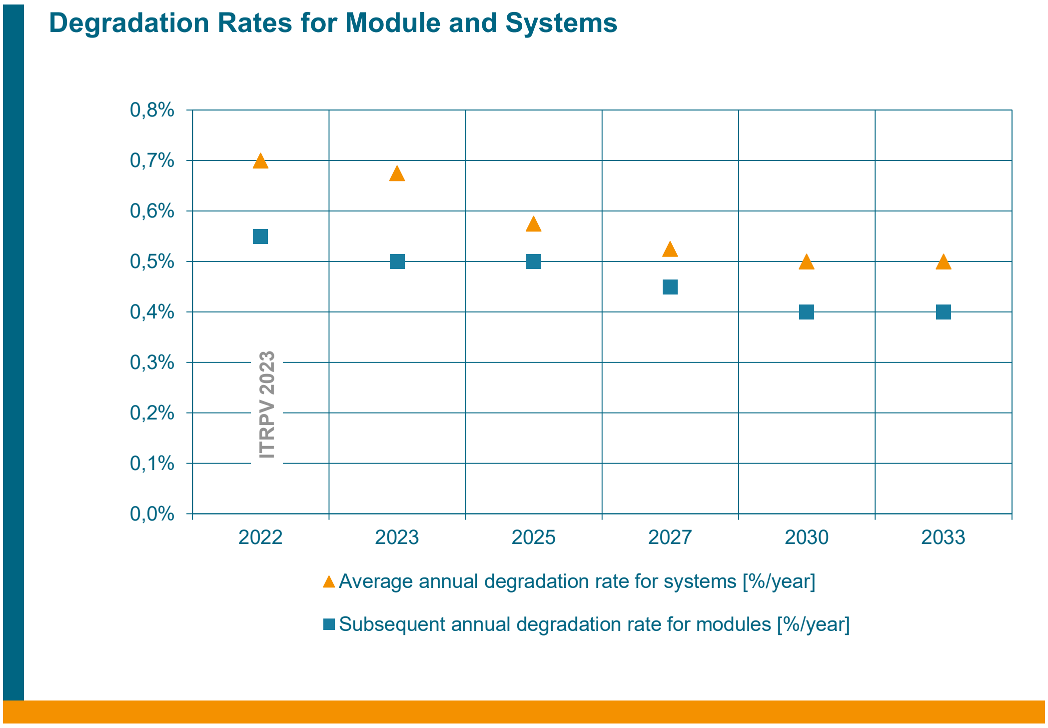


Fig. 71: Trend of modules and PV system degradation.

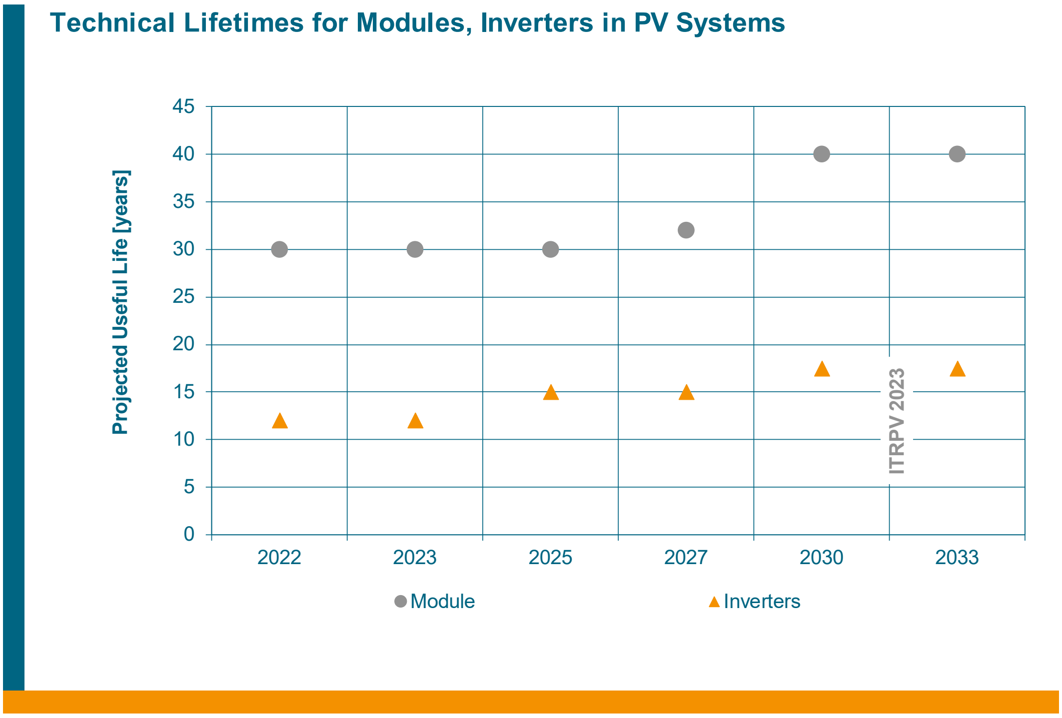


Fig. 72: Trend of technical lifetime of PV System electrical components.

Technical lifetime of modules is expected to be on average above the performance warranty shown in Fig. 65. Inverters technical lifetime is expected to increase from 12 years in 2023 to about 18 years in 2033.

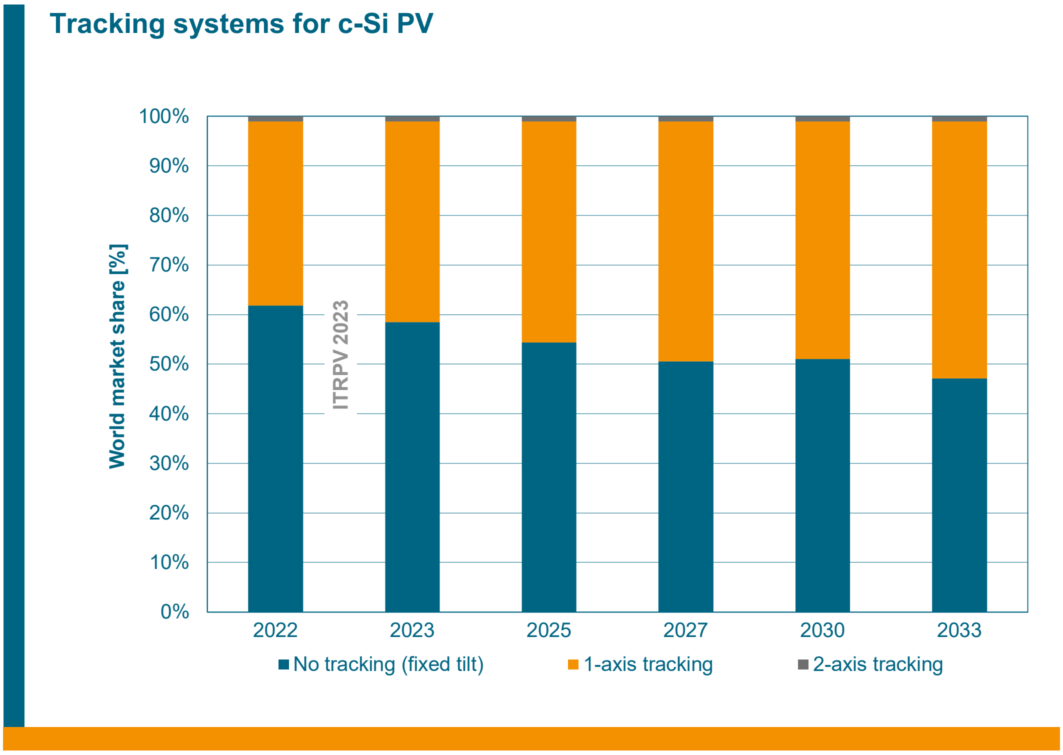


Fig. 73: Market share of tracking systems for PV power plant installations.

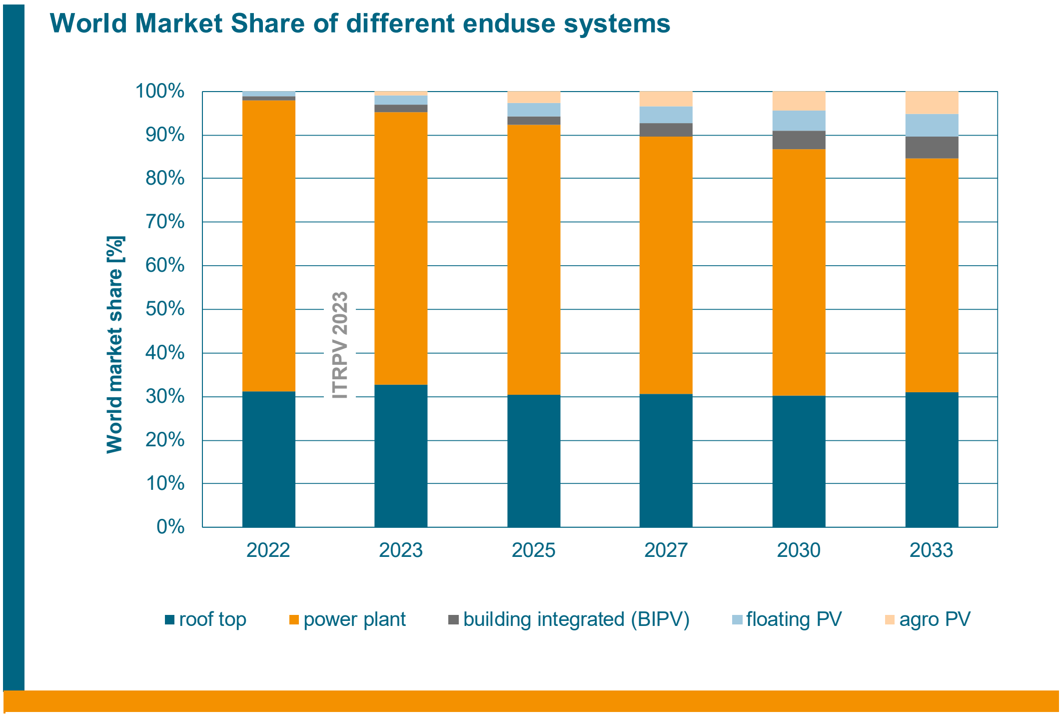


Fig. 74: Market share of different PV enduse systems.

Around 65% of PV systems are operated with 1500 V system voltage, the share of 1000 V systems is expected to shrink to 10% within the next 10 years. Fig. 73 shows the trend for tracking systems in PV power plants. In 2023 about 58% of systems have no tracking. 1 –axis tracking is expected to witness an increase in its market share, while 2-axis tracking is expected to stay a niche application with <1% also in future. The market share of different enduse systems is visualized in Fig. 74. Roof top systems are expected to stay stable at about 30% within the next 10 years.

Building integrated PV systems as well as agro PV, and floating PV are expected to gain market share while "classical" PV power plants will stay dominant at above 50% market share. PV installations will be more and more combined with storage systems. Fig. 75, 76, and 77 show the share for the different market fields of rooftop applications, commercial & small industrial (C&I) applications, and for power plant installations respectively.

Storage is expected to be more widely used within the next 10 years. In rooftop installations, the combination with storage will be dominating from 2030 onwards.

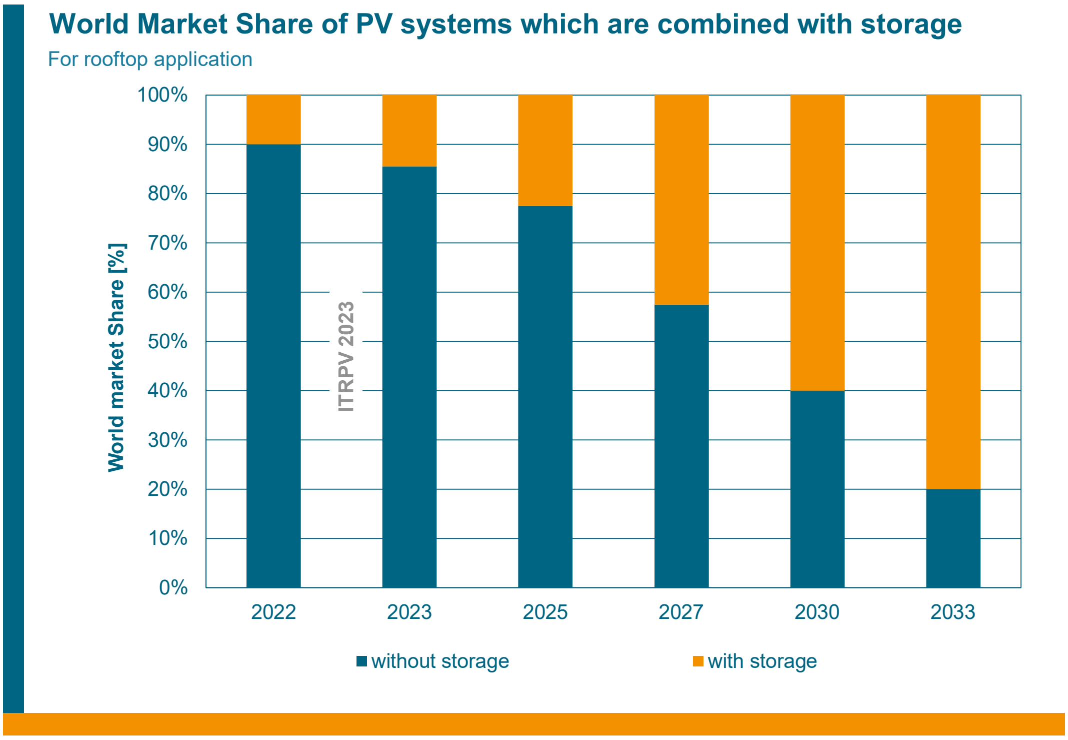


Fig. 75: Market trend of rooftop PV systems with storage .

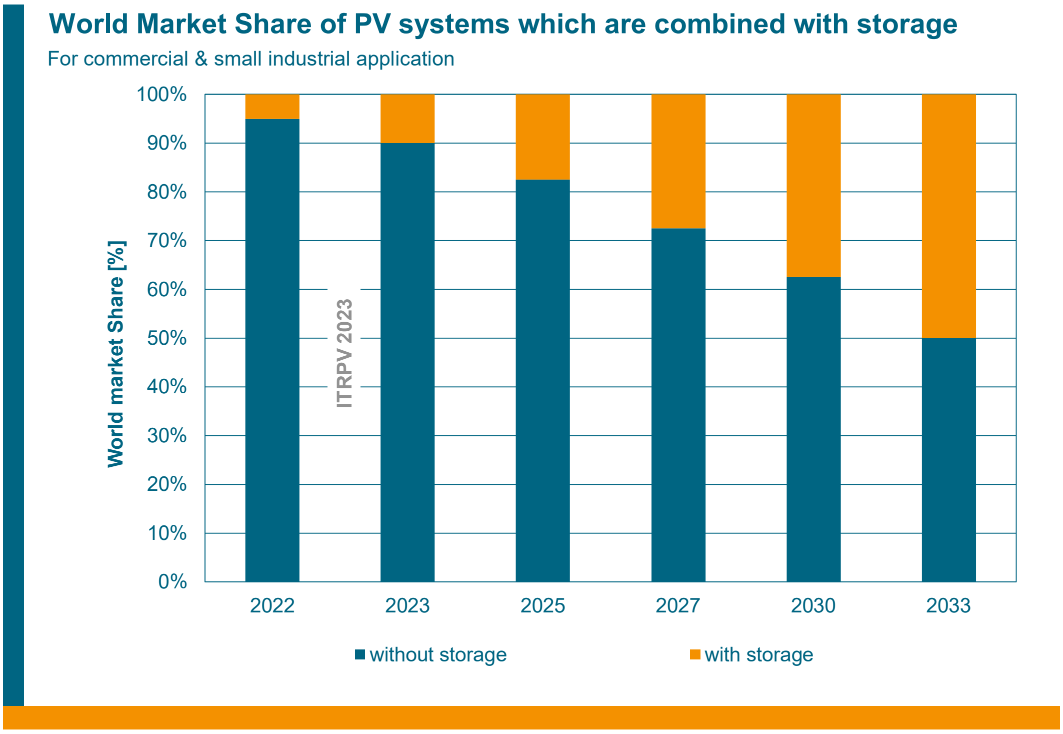


Fig. 76: Market trend for C&I PV installations with storage.

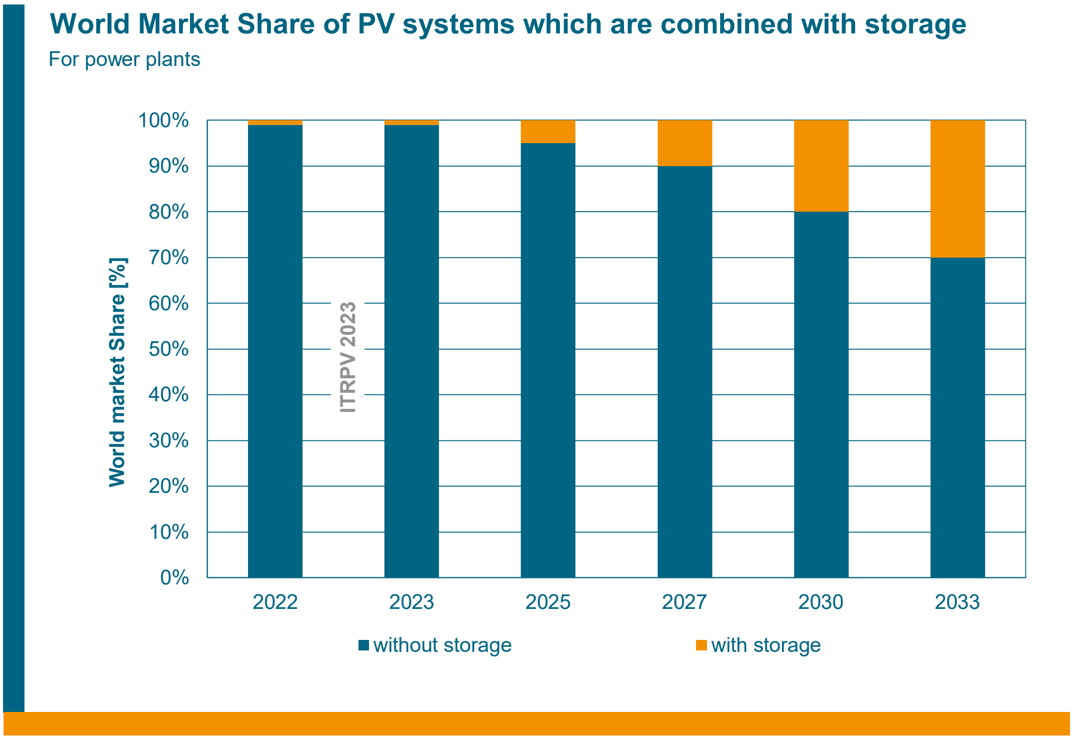


Fig. 77: Market trend for power plant installations with storage.

9.2. LCoE Calculation Section

The LCoE is a commonly recognized economic metric for comparing the relative costs of different renewable and non-renewable electricity generation technologies. Along with the system capital cost and the solar insolation level, LCoE is also dependent upon operations and maintenance (O&M) expenses, the project financing structure, the expected rates of return for debt and equity stakeholders, national and local incentives, and the usable service life of the system. We have used NREL's System Advisor Model (SAM) discounted cash flow structure to calculate 2022 benchmark and future scenarios of PV LCoE for large PV systems under different insolation conditions (see Fig. 78) [36, 37, 38].

Using the worldwide median capital costs for 2022, nominal LCoE values between 3.6 and 9.0 cents per kWh-ac are calculated across the range of solar insolation levels. Using the system capital trends from this year's ITRPV survey, nominal and unsubsidized LCoE is projected to be between 2.4 to 5.9 U.S. cents per kWh-ac in the year 2033 from the high (2,500 kWh-ac/kW-dc) to low (1,000 kWh-ac/kW-dc) insolation conditions. Improvements in product reliability and energy yield, lower operations and maintenance (O&M) expenses, lower financing rates, increases in system voltages and better power electronics, and more robust national and local incentives are all potential opportunities to further reduce PV system LCoE.

For our calculations we have assumed 25 years of usable system service life; however, it is expected that advances in module and BOS technology as discussed in this edition of the ITRPV and as shown in Fig. 72 will extend the service lifetime even longer. Longer system service life and lower system degradation rates as shown in Fig. 71 will make it possible to lower LCoE even further and help PV to become even more cost-competitive on a complete lifecycle basis.

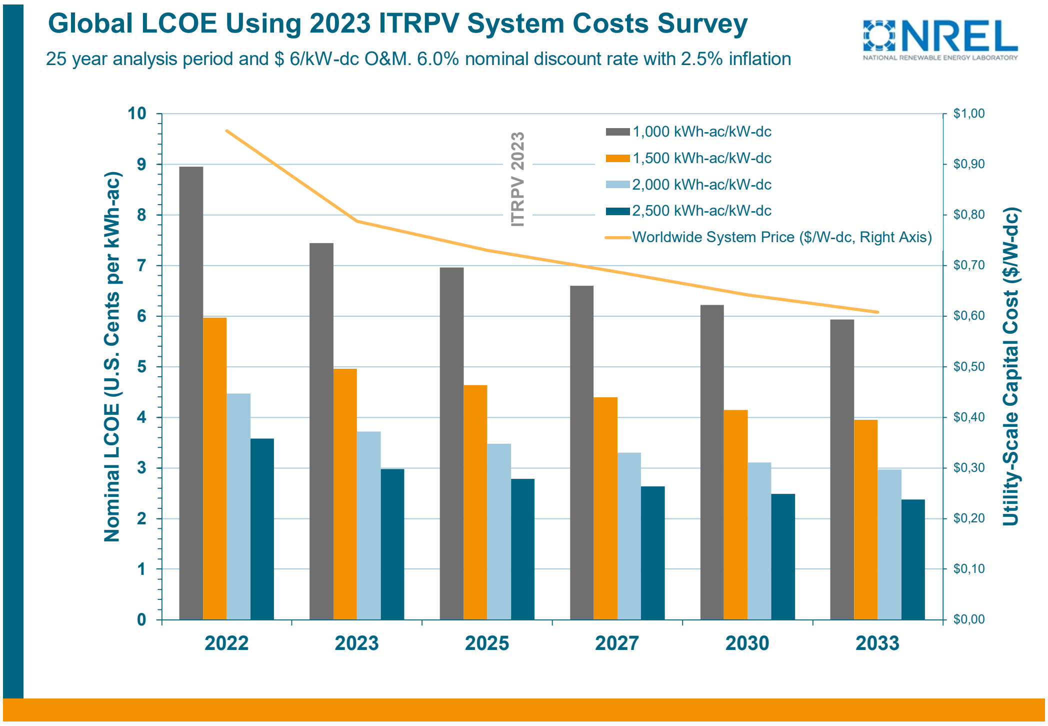


Fig. 78: Calculated LCoE values for different insolation conditions and median capital costs from the 2023 ITRPV survey. The calculations were performed using NREL's System Advisor Model (SAM) cash flow structure.

10. Outlook

10.1. PV learning curve

Chapter 3 reviews the learning curve status. Fig. 1 shows the price learning curve and the calculated price learning rate. The current learning rate is calculated to be 24.4% using all historic price data points from 1976 to 2022. However, considering only the data points from 2006 - 2022, the learning rate is 39.3% as shown in Fig. 79.

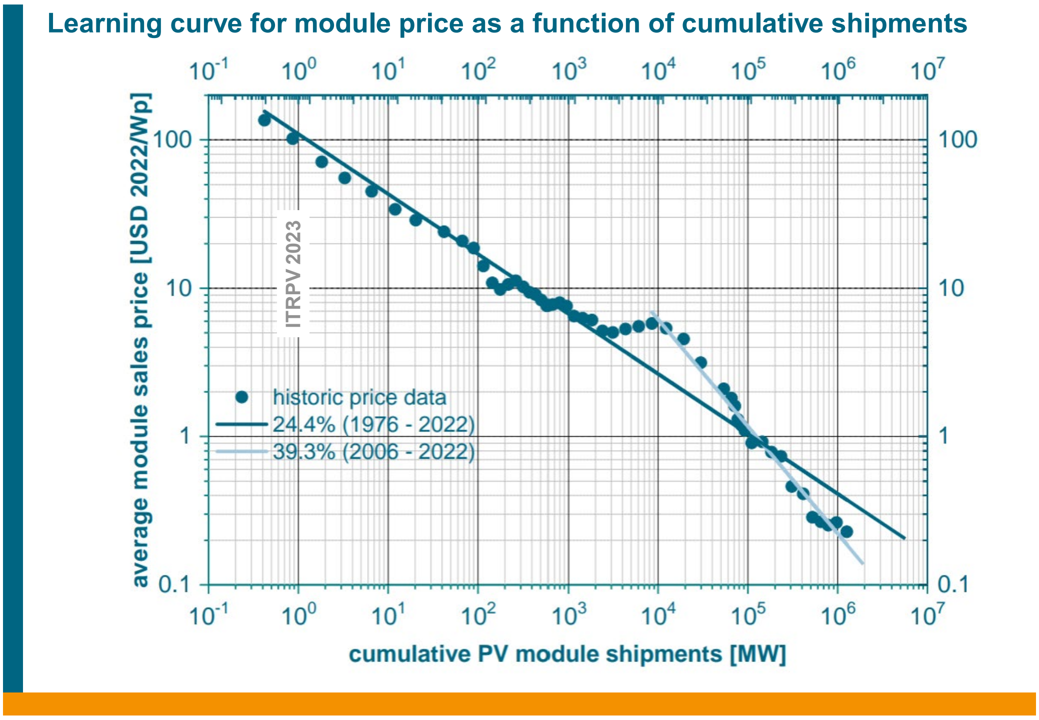


Fig. 79: Learning curve of module spot market price as a function of cumulative PV module shipments and calculated learning rates for the period 1976 to 2022 and 2006 to 2022, respectively.

The year 2006 was the last year of a longer period of silicon shortage. It marks the beginning of c-Si PV mass production in China and thereby the entry into a period of continuous capacity extensions after the scarcity situation of polysilicon and PV modules during the period between 2004 and 2006.

Based on the findings in the ITRPV we started in the 8th edition the analysis about the breakdown to the two basic learning contributors - module power learning and reduction of price (cost) per piece learning.

Tab. 1 summarizes average module efficiencies at different years. The price values were taken from the learning curve while module efficiencies between 2010 and 2019 were calculated, based on average module powers of p-type mc-Si and mono-Si modules reported by the ITRPV (3rd to 11th edition, [17]) in combination with a standardized module size of about 1.64 m² for 60 cell modules. The module efficiency of 1980 was found in [39]. Average module efficiencies for PERC modules in 2020 are assumed to 20% based on the ITRPV 12th edition and in 2021 to 20.9% in the 13th edition respectively. 2022 module efficiency is according to Fig 55.

Tab. 1: Yearly learning for module efficiency and price per piece based on module price data (2010 = 100%) [7, 8, 9], module efficiencies are calculated from ITRPV module power values (3rd to 11th edition) and from the 12th edition; 1980 module power is calculated from the efficiency indicated in [41].

Year over year learning

Year	1980	2010	2011	…	2019	2020	2021	2022
avg. Module power p- type rooftop: until 2019: ITRPV-data, 2021ff: calculated for 1.93m² = 1.134 m x 1.7 m (108 HC M10)	148	242	248		326	375	403	407
Module efficency 60/120HC/108HC [%], avg. Mod. area: 1.64 m² [5], 2019: 1.7 m², 2020ff. ITRPV efficiency	9	14.7	15.1		19.2	20	20.9	21.11
Module price [$2022]	44.92	2.09	1.3		0.27	0.25	0.26	0.23
Relative module price reduction [%]		95.34	37.77		6.5	5.47	-4.57	13.43
Module price (Wp-increase only) [$2022/Wp]		2.09	2.04		1.6	1.54	1.47	1.46
Module price (cost reduction per piece only) [$2022/Wp]		2.09	1.36		0.76	0.81	0.88	0.86

The trend to larger wafer formats as shown in Fig. 10 results in a variety module formats. Until 2019 mainstream module format was 60 full-cells / 120 half-cells. The corresponding averaged module area increased from 1.64 m² to about 1.7 m² in 2019 [40] and 1.8 m² in 2020 [17]. The module size for rooftop applications increased further according to Fig. 56,. For 2021 ff. we took 1.93 m² as average size of M10 108 HC modules (see also Tab. 1). The average module power is calculated to 403 Wp and 407 Wp respectively.

Fig. 80 shows the plot of Tab. 1 data points for efficiency learning and per piece learning, respectively. The corresponding calculated learning rates of 8% for efficiency learning and 15% for per piece learning indicate that the main contribution of the price learning arose from per piece reductions. The 2022 year end spot market price is ≈0.23 US$/Wp as discussed in chapter 4.

Learning curve for module price as a function of cumulative shipments

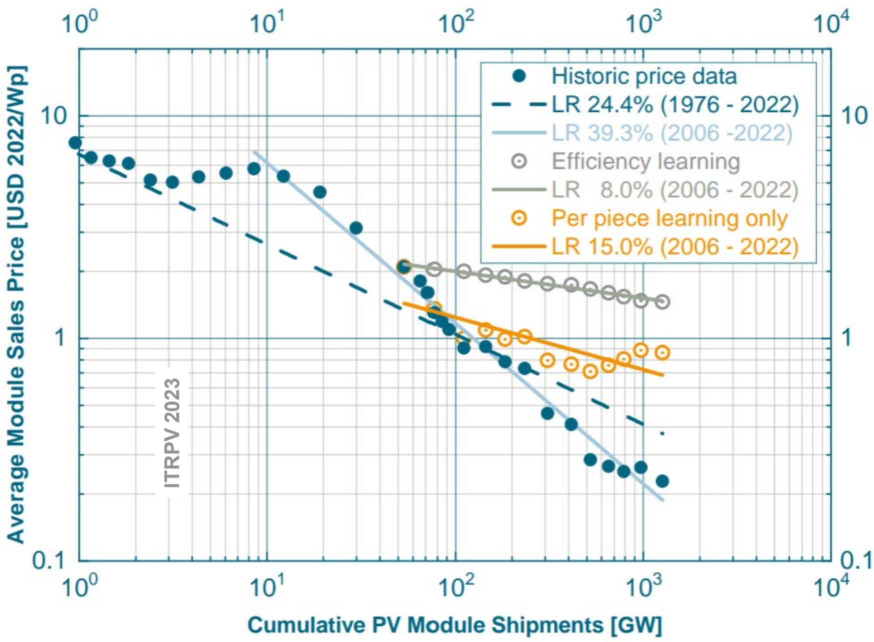


Fig. 80: Log-log plot learning curve of module spot market price as a function of cumulative PV module shipments; update on calculated learning rates for the period 1976 to 2022 and 2006 to 2022 respectively, calculated rates for Wp learning and per piece learning according to Tab. 1.

The high price increase in 2021 is the reason for the considerable reduction of the per piece learning compared to the calculation in the former editions. This analysis emphasizes again that only the combination of efficiency learning, and cost reduction grants the resulting learning despite the fact that per piece learnings in 2019 until 2021 were not in line with the learnings until 2018, mainly due to the introduction of the larger module formats and due to overall cost increases. Progress in per piece learning was detected again in 2022.

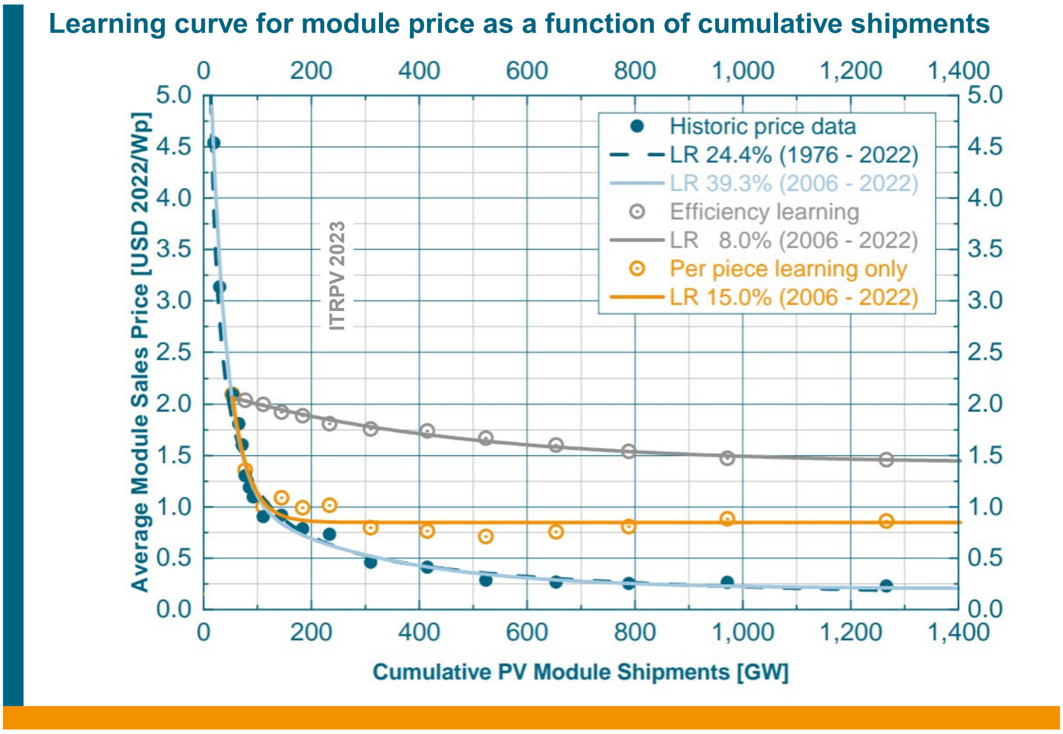


Fig. 81: Linear plot of Fig. 80.

Fig. 81 shows the data of Fig. 80 in a linear plot.

10.2. PV market development considerations

PV will play a key role in a future net zero greenhouse gas emission energy system that has to be installed until 2050 [41]. The most widely publicly discussed PV-related topics and trends are about installed PV module power (DC), module shipments, and PV generated electricity scenarios.

A look at the supplier side, to see the trend of the market for PV modules, cells, wafers, and polysilicon, is less spectacular, but it is essential for investment planning.

The analysis of the annual PV market development until 2050 started in the ITRPV 6th edition. In this 14h edition we continue to discuss the PV contribution in different scenarios of a global energy system based on up to 100% renewable energy: the scenario of Bogdanov et. al [42], the" Green Scenario" of the BNEF NEO2022 [43], the Sustainable Development Scenario (used for visualizing the regional breakdown) as well as the Net Zero Emission by 2050 scenario of the IEA WEO 2022 [44], and we recall a scenario of the ITRPV 9th edition, the mixed scenario [45]. The update of 2022 PV module shipments is considered in the context of all scenarios.

Details of the scenarios and the corresponding considered regions are summarized in Tab. 2.
Fig. 82 - Fig. 85 display these scenarios showing the calculated cumulative PV installation in 5-year steps, the corresponding 5-year average annual PV market without and with replacement after 25 years for the installations until 2025. The historic annual shipments are indicated according to Fig. 1 and Fig. 69.

We consider the following scenarios:

1. IEA scenario: (all sectors) — 15.5 TWp installed PV and ≈0.8 TWp avg. annual PV market in 2050, generating 27.0 PWh ≈37% of world energy supply according to [44].

2. BNEF scenario: (all sectors) — 17.4 TWp installed PV and ≈1.3 TWp avg. annual PV market in 2050, according to [43].

3. Broad electrification: (all sector) — 63.4 TWp installed PV and ≈4.5 TWp avg. annual PV market in 2050 generating 104 PWh ≈69% of global primary energy demand (including power & heat, transport, and desalination) [42].

4. Mixed scenario (all sectors) — 18 TWp of installed PV in 2050, generating 30 PWh according to [45].

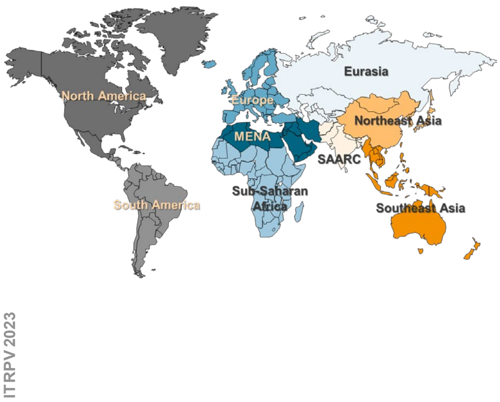
Scenarios 1, 3, and 4 are superimposing calculated results for different world regions.

Fig. 82 illustrates scenario 1 - PV based power generation figures, published in the IEA World Energy Outlook 2022 (WEO 2022), a current analysis about electrical power generation and consumption until 2050, based on assumptions about population growth and energy consumption trends [39]. It considers the limitation of global temperature increase to 1.5°C at the end of the 21st century. This "net zero emission scenario" assumes a PV installation of about 15.5 TWp being enough to cover 23% of global electricity generation in 2050. Energy yield in this scenario is assumed to be about 1.74 kWh/kWp. The average addressable market including replacements after 25 years is calculated to about 830 GWp in 2050.

Tab. 2: Summary of regional results of the different scenarios.

Summary of regional results for the different scenarios

Scenario	Region	Installed power 2050 [TWp]	PV Power generation 2050 [PWh]
IEA Scenario	Americas	2.0	
	AsiaPacific	6.5	
	MENA	0.8	
	Afrika	0.7	
	Europe	0.8	
	ROW	0.5	
	Net Zero adder	4.6	
	total	15.5	27.0
BNEF scenario	total	17.4	
100% Renewables	Sub-Saharan Africa	2.9	
	MENA	4.6	
	North America	7.0	
	Northeast Asia	17.8	
	SAARC	11.9	
	South America	2.3	
	Southeast Asia	5.3	
	Eurasia	2.6	
	Europe	8.9	
	total	63.4	104.0
100% Renewables	Africa + MENA	4.3	
	Americas	2.6	
	Asia	5.0	
	Europe	1.4	
	ROW	4.8	
	total	18.1	



Historic shipments plotted in Fig. 82 are above the projected addressable market of this scenario. WEO 2022 is still underestimating the market potential of PV installations from our point of view.

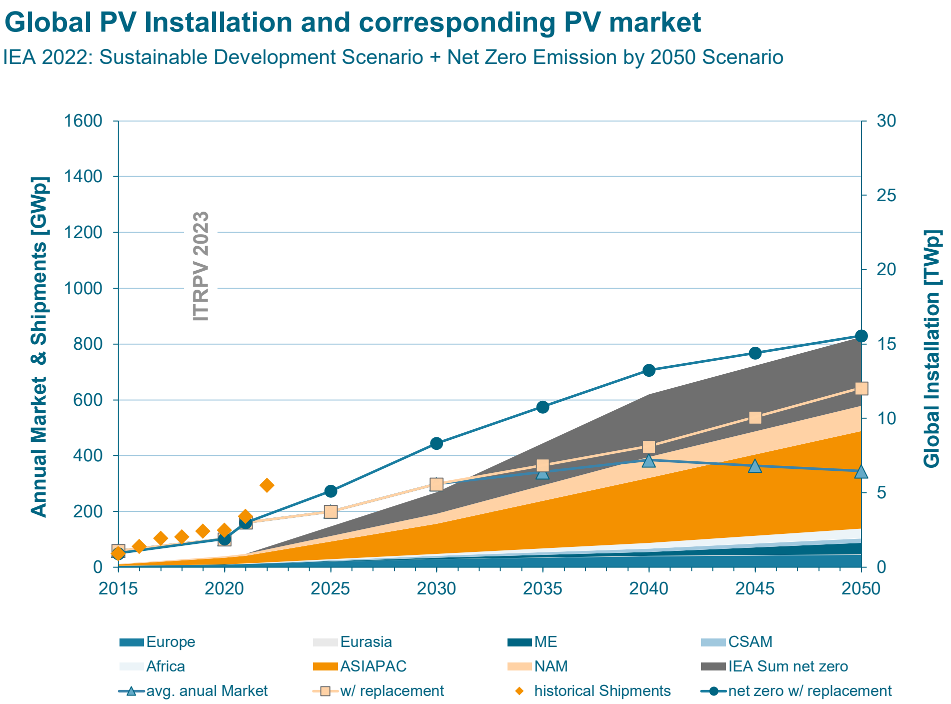


Fig. 82: Scenario 1 – IEA scenario: annual PV market and corresponding cummulated global installation of 15.5 TWp PV in 2050 and shipments with and without replacements after 25 years, according to [38].

Fig. 83 shows the updated BNEF NEO 2022 scenario. In 2050 17.4 GWp installed PV are assumed in this scenario. The annual PV market including replacements after 25 years of operation in this scenario is assumed to about 860 GWp without replacement in 2050. The historic shipments until 2022 are close to the projection. This scenario is more optimistic than earlier BNEF assumptions: close to three times of the assumption of the BNEF NEO 2020, discussed in the 12th edition.

Scenarios 3 considers the need of a net zero greenhouse gas emission energy system no later than 2050. PV will be the key technology to reach a 100% renewable energy and greenhouse gas emission free energy economy by 2050, considering the three main energy consumption fields of power & heat, transportation, and desalination for 9 major global regions as summarized in Tab. 2, a model presented in [42] and [46] is used.

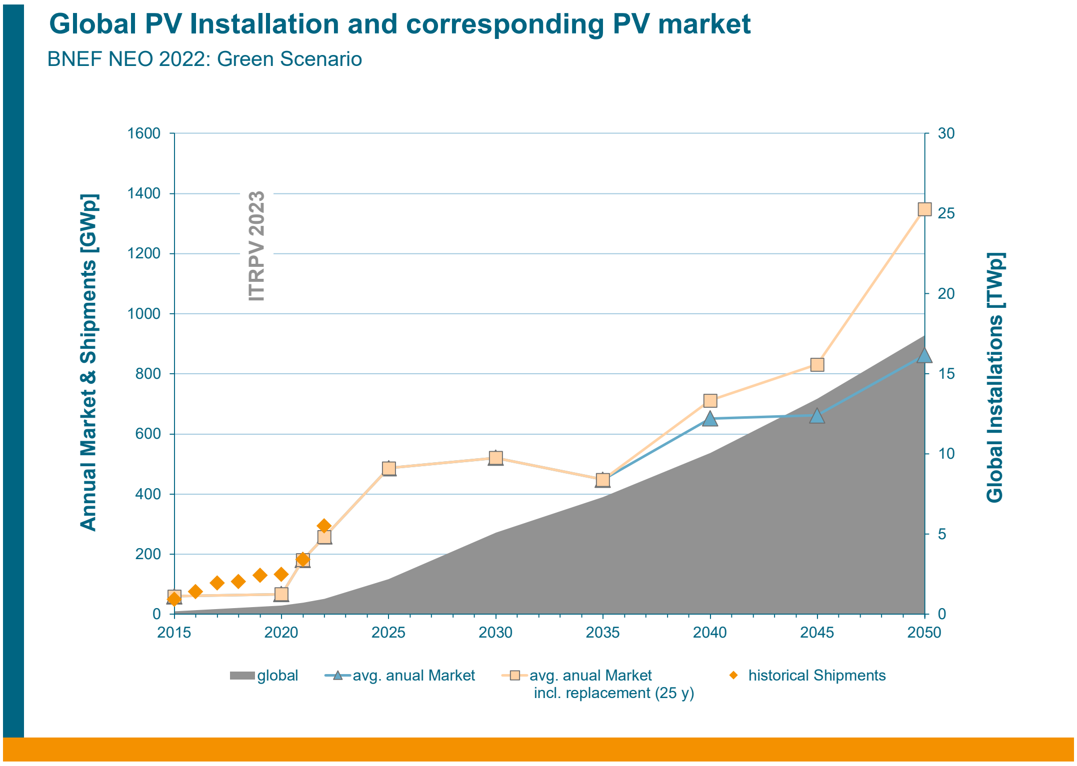


Fig. 83: Scenario 2 – BNEF scenario: annual PV market and corresponding cummulated global installation of 17.4 TWp PV in 2050 and shipments with and without replacements after 25 years, according to [39].

Fig. 84 shows the required PV installation trend to reach the Broad electrification scenario 4. This will be the path towards a zero-greenhouse gas emission economy in 2050. Scenarios 3 considers an average system energy yield of approximately 1650 kWh/kWp realized by power plant installations in higher insolation regions, also taking single axis tracking with higher yields into account. It is remarkable that the historic shipments are quite close to the required shipments in this scenario.

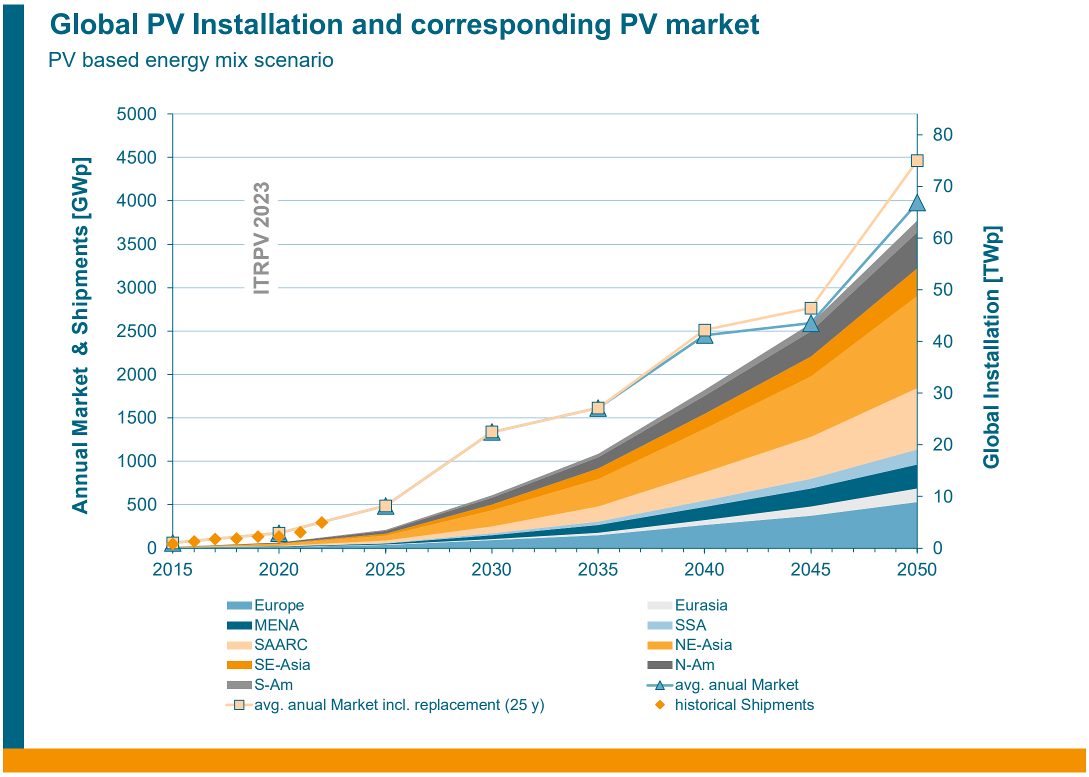


Fig. 84: Scenario 4: Cumulative installed PV module power and 5-year average annual market for global PV module installation of 63.4 TWp in 2050 in a zero greenhouse gas emission economy - broad electrification (see Tab. 2 and [42]).

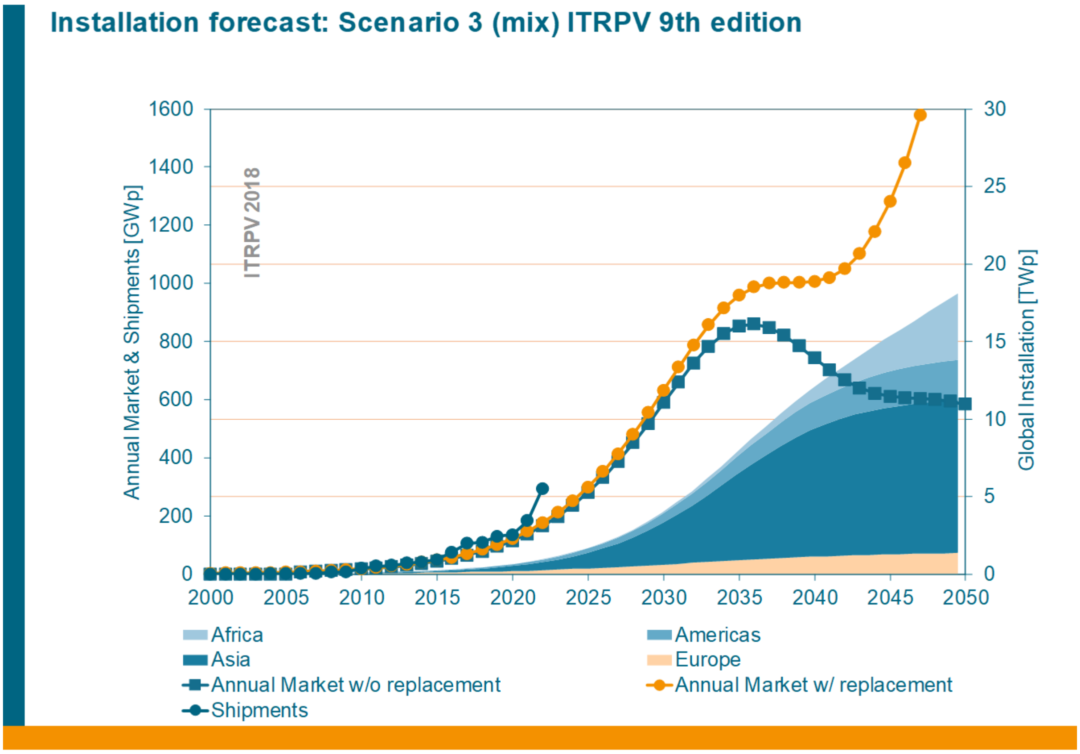


Fig. 85: Scenario 4: Cumulative installed PV module power average annual market for global PV module installation 18.1 TWp in 2050 (see Tab. 2 and [45]).

Fig. 85 shows a scenario we discussed in the ITRPV 8th together with the historic shipments. It is interesting to see that the shipments are also close to the projections until 2021 but last year's shipments are well above the expectations at that time.

All four scenarios show that there will be a formidable and increasing module market in the future. Production capacity is increasing continuously. The risk of volatile market situations due to over- and undersupply situations along the value chain is permanently present.

A continues increasing PV module demand is fuelled by the fact that PV electricity is about to become the cheapest source of electricity globally. Cheap PV electricity will drive power-to-X demand so that other energy sectors can also benefit from low-cost PV. Scenario 3 assumes a broad electrification for fulfilling the targets of the Paris Agreement for a least cost energy system.

Scenario 1 will be no challenge for the PV industry. Module capacity is forecasted to have reached 470 GW in 2021. So, 800 GW markets will be served even within the next years with existing technologies. Production capacities of above 1 TWp as discussed in Scenarios 2 and 4 seem to be manageable even with today's mainstream technologies. Production capacities significant beyond 1 TWp as in Scenario 3 and in a scenario by Verlinden [47] appear more challenging also regarding material consumption [47]. In parallel with the expected increase of PV production and installation, recycling will become more important in the future - as business opportunity and as challenge [48, 49, 50].

Improved tool concepts in cell manufacturing for production lines with matched throughput between front and backend, as discussed in chapter 6.2, will support future production capacity increase. Anyhow, a capacity increase beyond the 1 TWp level will require further improved production technologies. PV equipment suppliers have to support the installation of new production capacities. New c-Si capacities for cell and module will deploy n-type concepts TOPCon, and SHJ, as well as IBC. PERC p-type capacity will still take place mostly outside China. The n-type cell technologies should also be considered as possible upgrades for existing PERC lines especially in the case of TOPCon and for future c-Si based Tandem concepts.

The continued support of depreciated production lines, the replacement of worn-out equipment and the building of capacity expansions with smart factory approaches as discussed in chapter 8 will constitute considerable business segments to support the projected growth. All these facts emphasize the positive outlook for the whole c-Si PV industry.

The current ITRPV edition discussed possible trends and improvements in c-Si PV technology like increasing cell and module efficiency, increasing module power, more efficient usage of poly-Si and all non-Si materials as well as a higher utilization of all production capacities. All these measures will help manufacturers in their efforts to supply the market with highly competitive and reliable c-Si PV power generation products in the years to come. The price learning of PV modules will continue, and this will further push the LCoE reduction of PV systems.

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12. Acknowledgement

We would like to thank all our contributors. Only companies granted permission for the publication are listed here:

Itai Suez, **547 Energy**
Francesca Antoniolli, Paolo Fugolo, Marco Galiazzo, **Applied Materials, Inc.**
Juras Ulbikas, **Applied Research Institute for Prospective Technologies**
Steffen Wiedmann, **AXITEC Energy GmbH & Co. KG**
Johannes Bernreuter, **Bernreuter Research**
Lotfi Bounaas, Delfina Muñoz, **CEA/Liten – INES**
Javier Diaz Berrade, Jaione Bengoechea Apezteguia, Eugenia Zugasti Rosende, **CENER National Renewable Energy Centre**
Djoudi Bouhafs, **Centre de Recherche en Technologie des Semi-Conducteurs pour l'Energétique (CRTSE)**
Malte Vogt, Arthur Weeber, **Delft University of Technology**
Nabih Cherradi, **Desert Technologies**
Julien Dupuis, **EDF R&D**
Matthias Drews, **EKRA Automatisierungssysteme GmbH**
Robin Bedilion, Robert Flottemesch, Terry Jennings, Wayne Li, Cara Libby, Nicholas Pilot, Chris Powicki, **Electric Power Research Institute**
Imco Goudswaard, **Endurans Solar**
Arnulf Jäger-Waldau, Nigel Taylor, **European Commission Joint Research Centre**
Sebastian Schindler, **Fraunhofer CSP**
Baljeet Goraya, Anna Heimsath, Sven Kluska, Andreas Lorenz, Sebastian Nold, Ralf Preu, Anamaria Steinmetz, Sebastian Pingel, Dilara Maria Subasi, Birger Zimmermann, **Fraunhofer ISE**
Alexander Gerlach, **Gerlach New Energy Consulting**
Torsten Röder, **Grenzebach Envelon**
Klaus Ramspeck, **halm elektronik gmbh**
Ronny Bakowskie, Fabian Fertig, Markus Fischer*, Matthias Goldbach, Marco Göbel, Alexander Grimm, Matthias Junghänel, Friederike Kersten, Marcel Kühne, Ansgar Mette, Michael Mette, Jörg Müller, Kai Petter, Stefan Peters, Thomas Taubert, Anika Weihrauch, **Hanwha Q CELLS GmbH**
Björn Rau, Rutger Schlatmann, **Helmholtz-Zentrum Berlin für Materialien und Energie, PVcomB-Kompetenzzentrum Photovoltaik Berlin**
Bill Gao, Zhaohui Qu, Yunzi Jiang, **Heraeus Photovoltaics**
IBC SOLAR AG
Thorsten Dullweber, **Institut für Solarenergieforschung GmbH**
Joris Libal, **ISC-Konstanz e.V.**
Christopher Berge, **ISRA VISION GmbH**
Paul Ni*, **Jiangsu Akcome Science & Technology Co., Ltd.**
Nadia Foo Kune, **kiloWattsol SAS**
Zhang Lucy Han, Huang Ke, Zehao Zhang, Tian Xie, **LONGi Green Energy Technology Co., Ltd.**
Axel Metz*, **MBJ Solutions**
Oier Aliaga, **Mondragon Assembly S.Coop.**
Chi-Chun Li*, **Motech Industries Inc.**

Wolfgang Jooss, Julian Reichle, Mehul Raval, Oliver Voigt, **RCT Solutions GmbH**
Ulrich Jäger, **RENA Technologies GmbH**
Robert A. Gaiser, Manuel Höß, **Robert BÜRKLE GmbH**
Bianca Wattenberg, **SINGULUS TECHNOLOGIES AG**
Jason Yang, **Sino-American Silicon Products Inc., Yilan Branch**
Menno van den Donker, **Solarge B.V.**
Greg P. Smestad, **Sol Ideas Technology Development**
Armin Aberle, **Solar Energy Research Institute of Singapore (SERIS)**
Agata Lachowicz, **Sustainable Energy Center CSEM**
Hongqiang Qian, **Suzhou Talesun Solar Technologies Co., Ltd**
Karl Melkonyan, **S&P Global**
Sven Kramer, Michael Schäfer, **teamtechnik Maschinen und Anlagen GmbH**
Dirk Jordan, Michael Woodhouse*, **The National Renewable Energy Laboratory**
Guoqiang Xing*, **Tongwei Solar Co., Ltd.**
Gianluca Coletti, Arthur Weeber, **TNO Energy Transition**
Valerick Cassagne, Lars Oberbeck, Bruno Delahaye, **TotalEnergies**
Gianluca Coletti, Bram Hoex, **University of New South Wales**
Puzant Baliozian, Jutta Trube*, **VDMA Photovoltaic Equipment**
Mahdab Das, Ivan Saha*, **Vikram Solar Ltd.**
Richard Moreth, Christian Rosner, **VITRONIC Dr.-Ing. Stein Bildverarbeitungssysteme GmbH**
Sebastian Gatz, Eric Schneiderlöchner, **VON ARDENNE GmbH**
Erich Dornberger, **Wacker Chemie AG**
Assaf Hoz-Klemme, Bernhard Klöter, **WAVELABS Solar Metrology Systems GmbH**
Haitao Wang, Qi Wang*, **Zhejiang JinkoSolar Co., Ltd.**

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13. Imprint

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We would like to thank Dr. Markus Fischer in particular for his intensive support in writing the discussion.

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We would like to thank the steering committee consisting of chairs and editors for their cooperation.

Publisher
VDMA e. V.
Photovoltaic Equipment
Lyoner Str. 18
60528 Frankfurt am Main, Germany
Phone +49 69 6603 1979
E-Mail photovoltaik@vdma.org
Internet itrpv.vdma.org

Printing
Druck- und Verlagshaus Zarbock GmbH & Co. KG, Frankfurt am Main

Image Source cover picture
Institut für Solarenergieforschung GmbH (ISFH)

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Image: Institut für Solarenergieforschung GmbH (ISFH)

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